DESIGN, ANALYSIS AND FABRICATION OF AN ARTICULATED MOBILE MANIPULATOR

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By

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Under The Guidance of

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2013

Declaration

I hereby declare that this submission is my own work and that, to the best of my - knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

Date: **Elias Eliot**

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Certificate

This is to certify that the thesis entitled, "**DESIGN, ANALYSIS AND FABRICATION OF AN ARTICULATED MOBILE MANIPULATOR"** submitted by **Mr. ELIAS ELIOT**, Roll Number: 610ID302 to the **Department of Industrial Design, National Institute of Technology, Rourkela** is a bona fide work carried out by him under our supervision and guidance for the partial fulfilment of the requirements for the award of **Master of Technology Degree (Research).**

To the best of my knowledge, the matter embodied in the project has not been submitted to any other University or Institute for the award of any Degree or Diploma.

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ABSTRACT

The process involved in designing, fabricating and analysing a mobile robotic manipulator to carry out pick and place task in a dynamic and unknown environment has been explained here.

The manipulator designed and fabricated has a 5 – axis articulated arm for pick and place application but also can be reconfigured to do other tasks. The manipulator is built with its driving or power means fitted at the bottom to distribute the load effectively and also make handling easier. The mobile platform employs a novel suspension system which helps in relatively distributing the load equally to all wheels regardless of the wheels position giving the mobile platform better control and stability.

With reference to many available manipulators and mobile platforms in the market, a practical design is perceived using designing tools and a fully functional prototype is fabricated. The kinematic model determining the end effector's position and orientation is analysed systematically and presented.

Navigational controls are built using fuzzy logic and genetic algorithm with the help of the sensors' information so that the robot can negotiate obstacle while carrying out various tasks in an unknown environment. The path tracking for pick-and-place application is the overall target of this industrial manipulator.

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INTRODUCTION

Chapter 1

INTRODUCTION

"If every tool, when ordered, or even of its own accord, could do the work that befits it... then there would be no need either of apprentices for the master workers or of slaves for the lords." – Aristotle

This quote describes the inner essence of the word *Robot*. The term *Robot* brings to our mind various images from some of the best science fictions like Isaac Asimov's I-Robot and the most recent movies like Terminator and Wall-E. It was the Czech play-wright Karel Čapek who coined the word *Robot* in his 1920 play *Rossum's Universal Robots (R.U.R)* and *robota* in Czech means worker or serf or peasant. But if we look into the history we can see that as early as in 1500's Leonardo Da Vinci drew sketches of a human like robot, similarly Jacques de Vaucanson in 1700's built automaton inventions and this brings to our mind a question, why man is so keenly interested in designing and building robots or what purpose does it serve in human life?

In various ways robots can be used and applied in our day to day life. But these applications and uses can be broadly categorised into the following three:

- To do jobs that are dangerous.
- To do jobs that are repetitive, boring, stressful and laborious.
- To do jobs that aren't pleasing to do or are menial or people do not want to do.

Over the years there has been a shift in the visual understanding of the word robot, i.e. from mechanical human-like servants to whatever shape it is given to do a particular job. Thus almost any mechatronics device that is controlled by a computer and has a certain degree of autonomy can be called a robot. By accepting this reality man could achieve high levels of innovation in the field of robotics and create numerous machines that are purpose oriented and make his life simple.

A robot is defined in numerous ways by different people and organisations. One of the most widely accepted definitions is given by Robot Institute of America (RIA): *A robot is a reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks.*

The fact that robots can be reprogrammed is the highlight of the said definition. This reprogrammable ability allows the robot to adapt to different environments in a suitable manner and also be utilized as required. Factors like improved precision, better productivity, decrease in labour cost, increased flexibility and better working conditions are few commonly cited advantages for introducing robotics in industry. They can be found in automobile industries, medical field, space and research laboratories, manufacturing and processing industries, etc.

1.1 Basic Definitions in Robotics

Degree of Freedom (d.o.f.)	:	This is the number of independent coordinates necessary to completely specify the device in some coordinate frame.
Manipulator	:	An electromechanical device used to handle materials without direct contact.
Anthropomorphic	:	Non-human objects attributed with human characteristics.
End-Effector	:	A tool, a gripper or any other device attached to the end of a robotic arm/manipulator, for realising useful tasks.
Workspace	:	A volume in space where an end-effector can reach, both in position and orientation.
Position	:	The location of an object in space at a translational locus.
Orientation	:	The location of an object in space at a rotational or angular locus, i.e. the roll, the pitch and the yaw angles.
Pose	:	This is an instance when both position and orientation are considered.
Link	:	The rigid body of the robot which is connected together.
Joint	:	The links of a robot are interconnected to one another by joints.
Kinetics	:	The study of motion without reference to the underlying force structure
Dynamics	:	The study of motion in a body describing the behaviour of force/torque acting on it.
Actuator	:	The parts which provide motion to the robot by converting energy.
Sensor	:	Devices that collect certain information regarding the robot's environment or internal components which are useful in controlling it.

1.2 Robotic Arm/Manipulator

Basically industrial robots are not androids that mimic human, but they are designed with resemblance to a human hand; and are also incapable of self-movement. Accordingly these industrial robots are referred to as robotic arms or more technically robotic manipulator. These robotic manipulators are broadly classified based on their: drive technologies, work-envelop geometries and motion control methods.

Classification based on drive technologies is the most basic grouping. This is mainly involved with the source of power which drives the links of the robot; most popular being electrical, hydraulics and pneumatics. Depending upon the requirement different industrial robots possess different drive technology, sometimes two or more different types of drive technologies are combined together to achieve some task.

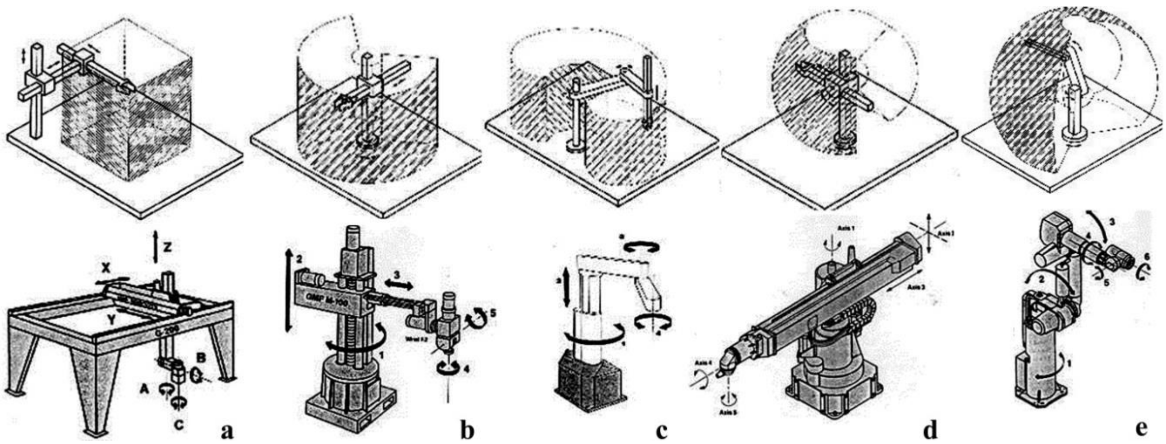


Fig.1.1 Geometry of the manipulator's work-space.

Work-envelop of a robot is the locus of points in three-dimensional space it can reach. With the help of numerous links and joints these points in space can be reached by the manipulator. The most basic joints are revolute and prismatic joints. Depending upon joints used in a robot the geometry of the work-space of the manipulator is defined and accordingly they are named as following: Cartesian robots (*Fig.1.1 a*), cylindrical robots (*Fig.1.1 b*), spherical robot (*Fig.1.1 c*), SCARA robot (*Fig.1.1 d*) and articulate robot (*Fig.1.1 e*). Classification based on the methods used to control the motion of the end effector is another fundamental one and the two commonly used techniques are point-to-point motion and continuous path.

1.3 Mobile Robotic Platform

With all these advancements in robotic manipulators they suffer from a very vital disadvantage; which being the lack of mobility. To overcome this shortcoming numerous mobile robots are being designed to mimic various types of motion in nature, namely: sliding, running, crawling, jumping, rolling etc. Of all the designs available the wheeled robot is the most frequently used.

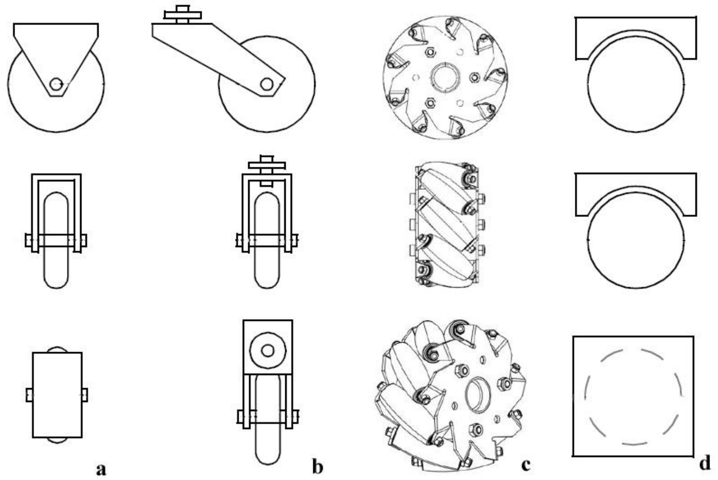


Fig.1.2 Types of Wheels.

Wheeled robots are classified depending on the type of wheel used. Different wheel types include: Fixed standard wheel (*Fig.1.2a*), Steered standard wheel, Castor wheel (*Fig.1.2b*), Swedish wheel (*Fig.1.2c*) and Spherical wheel (*Fig.1.2d*). The wheel-design and wheel-geometry play an important role in the stability, manoeuvrability and controllability of the robot. The stability of a mobile robot can be decided by the number of wheels used for its motion. Though the minimum number of wheels required for stability is two, under ordinary circumstances we rely on three or more wheels for better stability. Controllability of a mobile robot is the inverse of its manoeuvrability. More manoeuvrable the robot becomes, it is more difficult to control as accuracy becomes less. In several instances, the systems combining manipulation and mobility capabilities require coordination of the robotic arm and the platform, which is a specialty of mobile manipulation.

1.4 Objectives and Scope of the Work

In view of the above aspects, it is necessary to understand and analyse the mobile robots in industrial environments. Thus the principal objective of the work described in this thesis is to design and fabricate a mobile articulated robotic arm for pick and place application which could also be easily reconfigured to do other tasks.

By considering various commercially available robotic kits, it is planned to design and fabricate a five-axis articulate robotic manipulator with a mobile base having four fixed standard wheels. Kinematic analysis and path control of this robotic platform is also carried-out.

1.5 Outline of the Thesis

The processes involved in designing, analysing and fabricating a mobile robotic manipulator have been broadly divided into 8 chapters. Following the introduction, in chapter 2 a review of various literatures pertaining to mobile robotic manipulator design, fabrication, kinematic analysis, navigational techniques and experimental procedures have been stated.

Chapter 3 and Chapter 4 deal with the design specification and concept building of the mobile manipulator respectively. A detailed study of the requirements of a mobile robotic manipulator resulted in a precise design specifications and a concept model was built in accordance with this specifications. Chapter 3 also deals with the kinematics of both the mobile robotic platform and the articulated robotic manipulator separately.

The processes involved in building the robot have been elucidated in chapter 5. Various fabrication procedures involved in the making of the robot, the materials used and the cost of manufacturing are stated in this chapter.

Chapter 6 and Chapter 7 describe, few experimental trials conducted using the robot and artificial intelligence techniques implemented on the robot to test the navigational capability using various sensors, respectively.

The conclusion and future scope of the work is the final chapter of the thesis. A brief note on patent works has also been mentioned in the 8th chapter.

ANALYSIS OF PRIOR RESEARCH

Chapter 2

ANALYSIS OF PRIOR RESEARCH

Literature survey was conducted to obtain some insight into various factors relating to robotic manipulators, mobile robots and also kinematic analysis of robotic systems.

The history of industrial automation is characterized by periods of rapid change in popular methods. Either as a cause or an effect, such periods of change in automation techniques seem closely tied to world economics. Use of the industrial robot, which was identified as a unique device in the 1960’s along with computer aided design (CAD) systems and computer aided manufacturing (CAM) systems, characterizes the latest trends in the automation of the manufacturing process.

2.1 Mobile Manipulators

Several authors studied the industrial robots independently as complex manipulator arms and mobile mechanisms carrying simple linkages. Goldenberg et al. [1] presented an explosive disposal robot and described various design aspects and innovative technologies used in it. Lee et al. [2] recently presented a design of a mobile welding robot based on the workspace analysis. This is developed to use inside the ship hulls and the task oriented workspace has been increased by creating a moving base. Volpe et al. [3] provided a system overview of the Mars Rover Prototype, Rocky 7. They have described all system aspects of mechanical and electrical design, computer and software infrastructure, algorithms for navigation and manipulation, science data acquisition and outdoor rover testing. RedZone Robotics Inc. created the Pioneer robot [4] which was designed to explore the Sarcophagus at Chernobyl. This robot made out of unique materials could overcome severe radiation inside the reactor and retrieve information from the blown reactors.

Xu et al. [5] present a novel mobile manipulator concept called the Dual - Use Mobile Detachable Manipulator, for early construction and maintenance tasks in lunar stations.

Ben-Tzvi et al. [6] present a mechanical hybrid mobile robot with a novel design paradigm having a combination of parallel and serial links. This design can provide both locomotion and manipulation capability simultaneously and interchangeably.

Moosavian et al. [7] proposed a hybrid serial parallel mobile robot, which has a serial manipulator to handle objects and a parallel mechanism for navigation.

Liu et al. [8] describe a mobile robot which can be used to pick litchi fruit and shows how it can speed up the plucking process and also reduce human interference.

Manjunath et al. [9] present the design and fabrication of various parts of a mobile manipulator. This indigenous robotic arm has 4 axes of rotation and is run by a personal computer using java language.

A mini mobile robot named *Aggie Rover* was constructed and tested by Song et al. [10]. This system consists of three parts: base, arm and head, which can be remotely controlled separately and simultaneously

MobileRobot's PIONEER [11] is a modular-4 wheel driven mobile robotic platform with versatile application. It offers various options like a gripper or an on-board camera for both indoor and outdoor application. It is also equipped with a sophisticated laser mapping and navigation package, which can read, understand and map an area very accurately.

2.2 Robotic Arm/Manipulator

Tanii et al. [12] explain an interesting mechanism for a robotic arm. Alpha II is a five axis articulate robotic arm manufactured by Microbot [13] which has a variety of standard or specialized gripper mechanisms. It is a low-cost robot system designed specifically to help manufacturing operations management, improve productivity by automating low-level tasks that human workers find hazardous or difficult to repeat accurately for long periods of time.

Rhino XR-3 [14] is also a five axis articulate robotic manipulator. This robotic manipulator has a rugged open design, which makes it very easy to study. All successive works on this project has been carried out using this robot as a major reference.

Islam et al. [15] describe the process involved in designing and building a prototype for a 5 DOF robotic arm controlled by a microcontroller which is interfaced to a computer. This system has a 2 fingered gripper as an end effector.

Yamamoto et al. [16] implemented a control algorithm on real mobile manipulator robots such that according to their manipulability the manipulator is always positioned at the preferred configurations.

Krainin et al. [17] developed a system to build 3D surface model of objects grasped by a robot by moving it in front of its depth camera.

Hao et al. [18] introduce the design and development of a PC Based Robotic Arm (PC-ROBOARM) of 6-DOF based on PUMA joint arm model. The robotic arm is modelled with three-links connected with suitable servomotors at the joints.

Soares et al. [19] describe a robotic workstation based on the Rhino XR4 robot. This locally developed user interface helps in programming the robot and conducting various experiments on kinematics trajectory following manipulation task, visually guided movements etc.

2.3 Kinematics of Robotic Manipulator

The kinematic modelling and analysis of a 5-axis stationary articulated robotic arm has been conducted by Manjunath [20]. Using C++ language, it shows visually the kinematic model incorporating obstacle avoidance algorithms for the pick and place operation.

De Xu et al. [21] systematically analysed the forward and inverse kinematics of a five DOF manipulator and suggested an analytical solution for the manipulator to follow a given trajectory while keeping the orientation of one axis in the end-effector frame.

Huang et al. [22] developed a 6 DOF manipulator and have conducted an inverse kinematics on it, calculating the arm trajectory through geometrical analysis. Also, Iqbal et al. [23] and Deshpande et al. [24] built a 6 DOF robotic manipulator and analysed its workspace. Using the robotics tool box in MATLAB the kinematics problems of the robot have been addressed. DH parameters are used to predict the forward kinematics of the manipulator and using the inverse kinematics the joint angle of the arm is calculated.

Artemiadis et al. [25] proposed a biomimetic approach for solving inverse kinematic problem of redundancy resolution for robotic arms.

Zanchettin et al. [26] have presented a study on how to exploit the kinematics of a human arm and utilize it in a robotic controller. This experimental approach studies and synthesizes the motion of human arm.

Wu et al. [27] present synthesis theory and geometric analysis for quotient kinematics machines (QKMs). QKMs have a unique and well-defined kinematic structure and are often categorized into hybrid kinematics machines (HKMs).

2.4 Suspension System for Mobile Platform

Regarding design of mobile platform, Campion et al. [28] have presented an analysis on the kinematic and dynamic models of wheeled mobile robots. Reimer [29] discusse~~s~~ a novel suspension system for vehicles which helps in equally distributing the load to all the wheels, irrespective of its position. Similarly, Bickler [30] present a rocker and bogie suspension mechanism which is currently being used by NASA on their Mars Rovers. Also, Crockett [31] gives a detailed description of a unique suspension system highly useful for off-road purpose vehicles.

A new type of suspension system for the lunar rover was proposed by Bai-Chao et al [32]. The suspension system is designed to facilitate climbing up obstacles, adapting to terrain, traveling smoothly, and distributing equally the load of cab to wheels. Tani et al. [33] built an active suspension four-wheel model and conducted experiments for the body attitude control during a run over a model rough road.

2.5 Mobile Robotic Platform

Cordes et al. [34] introduce a locomotion mode for the planetary rover Sherpa, having four wheeled-legs, each providing a total of six degrees of freedom. The design of the active suspension system allows a wide range of posture and drive modes for the rover.

The configuration combination design method of wheel-legged lunar rover proposed by Wang et al. [35] considered the mobile mechanism of wheel-legged lunar rover as three sub configurations: wheel-legged mechanism, suspension and bodywork.

A general approach on kinematic modelling of all-terrain vehicle traversing on uneven surface has been done by McDermott et al. [36]. This model is developed for full six degree of freedom. Chang et al. [37] have done kinematic modelling for a six wheeled robot that can move on uneven terrain based on Wheel-Centre modelling. This mobile robot incorporates a rocker bogie mechanism.

Tarokh et al. [38] proposed a systematic, data-driven method for kinematics modelling of high mobility wheeled rovers traversing uneven terrain. The method is based on the propagation of position and orientation velocities starting from the rover reference frame and going through various joints and linkages to the wheels. Similarly Tarokh et al. [39] have described a method for kinematic modelling of the Rocky 7 Mars rover. Also, simulation results are provided for the motion of the Rocky 7 over several terrains, and various motion profiles are provided to explain the behaviour of the rover by Tarokh et al. [40].

Gajjar et al. [41] discussed the kinematics and mechanical design aspects of a unique rover configuration for Mars exploration along with comparisons with the contemporary rover wherever needed. Rubio et al. [42] present two methods to obtain the inverse kinematics of a mobile robot.

2.6 Kinematics of Wheeled Robot with Skid Steer Mechanism

Skid Mechanism steering is achieved by differentially varying the speed of the lines of wheels on different sides of the vehicle in order to induce yaw. Shuang et al. [43] present a four wheel drive electric vehicle applied with skid steering. The vehicle model has 3-DOF, longitudinal, lateral and yaw direction, irrespective of suspension. The semi-empirical tire model is used in this vehicle and the longitudinal and lateral tire force can be calculated by slip ratio directly.

Mandow et al. [44] worked on improving real-time motion control and dead-reckoning of wheeled skid-steer vehicles by considering the effects of slippage, but without introducing the complexity of dynamics computations in the loop.

Wang et al. [45] developed a kinematic and dynamic modelling scheme to analyse the skid-steered mobile robot. A model for wheel/ground interaction was created and the robot's motion stability was analysed.

A practical mathematical formulation for solving inverse and direct kinematics is provided by Martinez-Garcia et al. [46]. Similarly Arslan et al. [47] present a robust motion control of a four wheel drive skid-steered mobile robot. Kang et al. [48] have described an autonomous driving control algorithm based on skid steering for Robotic Vehicle with Articulated Suspension. The driving control algorithm consists of four parts; speed controller, trajectory tracking controller, longitudinal tire force distribution and wheel torque controller to keep slip ratio at each wheel below a limit value.

A mathematical model of a 4-wheel skid-steering mobile robot is presented in a systematic way by Kozlowski et al. [49] by considering the robot as a subsystem consisting of kinematic, dynamic and drive levels.

2.7 Mobile Manipulator Planning and Control

Gao et al. [50] discussed the development of mobile manipulators, its aspects of motion planning and coordinated control between mobile platform and manipulator in recent years.

Padios et al. [51] presented a new frame work of kinematics of mobile manipulators and compared it with that of conventional robotic arms. Moreover, Padios et al. [52] present two approaches: one is based on global instantaneous kinematics for the whole system and the other follows a decomposition approach that requires trajectory planning for the platform.

Bayle et al. [53] proposed a systematic modelling of the non-holonomic mobile manipulators built from a robotic arm mounted on a wheeled mobile platform. This modelling offers unambiguous definitions and models to the designer of kinematic control laws.

Dubowsky et al. [54] present an effective method that models a mobile manipulator's spatial dynamic behaviour by considering the nonlinear dynamic characteristics which result from its manipulator's gross motions, accounts for spatial vibrations due to the distributed mass and flexibility of manipulator and vehicle, and includes the effects of the manipulator's and vehicle's control systems

Hirose et al. [55] have studied the fundamental design considerations for a planetary rover and have proposed a rhomboid four wheeled vehicle arrangement as a mechanism to manifest terrain adaptability compared to six wheels.

Stable motion planning for a wheeled mobile manipulator during heavy object manipulation tasks is investigated by Alipour et al. [56]. It is assumed that the initial and final poses of a heavy payload are specified and appropriate trajectories for multiple robotic arms relative to the moving base are planned without considering the postural stability of the system.

Lindemann et al. [57] describe the mobility assembly which is the mechanical hardware that determines the vehicles mobility capability. The details of the design, test, and performance of the mobility assembly are shown to be highly successful.

Hernandez-Herdocia et al. [58] integrated two Barrett WAM arms on top of a Segway RMP mobile base by putting together power sources, computers, and distributed software systems. Instead of using locally engineered and built components, they used commercially available components to assemble a mobile manipulator.

Farelo et al. [59] have presented a mobile manipulator which utilises its mobile navigation capability to keep the manipulator’s end effector stationary for activities of daily living like keeping a spring loaded door open, etc.

HELPMATE, a mobile robot by Transitions Research Corporation [60] was created to help in hospital transportation tasks. It has various on-board sensors for autonomous navigation in the corridors. The main sensor for localization is a camera looking to the ceiling. It can detect the lamps on the ceiling as references or landmarks.

Quick-change system is a device that when attached to the wrist of a robot, increases its ability to automatically change the grippers/end-effectors when necessary. Meghdari et al. [61] has presented one such quick-change system which enables the arm to use other end-effectors.

2.8 Navigational Techniques Based on Fuzzy Set Theory & Genetic Algorithm

Autonomous mobile navigation in uncertain and dynamic surroundings requires the robot to have good adaptive and perceptive capability, and extensive researches have been carried out in the field of navigational techniques using artificial intelligence to achieve this. Across the globe researchers use different techniques to automate their robots, here we will discuss few research works carried out in the field of Fuzzy Set Theory and Genetic Algorithm, two AI techniques which are implemented into the robot presented here.

In mid-sixties Lotfi Zadeh introduced the fuzzy set theory and published a paper on the same [62].Hoffmann [63] provides an overview of evolutionary learning methods for the automated design and optimization of fuzzy logic controllers.

Reactive control strategies strongly rely on the sensed information from the robots surrounding. Thus, imprecision and uncertainties in perception from sensors have to be considered [64]. The numerical process variables and the set-points [65] are provided with a smooth interface by the membership functions defining the linguistic terms. E. H. Mamdani's [66] work on fuzzy control application resulted in extensive research in the field of stability analysis of fuzzy systems.

To obtain required dynamic behaviour an external dynamic filter must be used in the controller [67].The knowledge base stores the control protocol in the form of if-then rules and these rules are based on qualitative knowledge [68].

While using mobile robots in unstructured, unknown and dynamic environment, intelligent control plays a vital role. The overall task is divided into subtasks reducing the task complexity of the intelligent control. These subtasks acting on the output from the sensors are called behaviours. Thus by reducing the task complexity in behaviour-based approach, the responsiveness to the surroundings can be increased [69].

Doitsidis et al. [70] present a two-layer fuzzy logic controller designed for 2-D autonomous navigation of a skid steering vehicle in an obstacle filled environment. The first layer provides a model for multiple sonar sensor input fusion and the second consists of the main controller that performs real-time collision avoidance while calculating the updated course to be followed by the vehicle. Boukattaya et al. [71] have presented a dynamic redundancy resolution technique for mobile manipulators using a position fuzzy controller.

Genetic Algorithms (GAs) have been used in solving many optimization problems successfully since its appearance in 1975 [72].The parallel search feature and the ability to quickly locate high performance region [73] contribute to the success of GAs on many applications.

Matellan et al. [74] have proposed autonomous robot navigation based on GA adapting basic reactive behaviours. Similarly, Ming et al. [75] have used GA for mobile robot path planning.

Using GA they adjusted the membership functions associated with the linguistic labels that defined the variables of a rule based control system.

Using GA Noguchi et al. [76] developed an optimal work path for an agricultural mobile robot, optimising the time series of the steering angle. The navigation of an autonomous intelligent agent by implementing an extended multi-population genetic algorithm (EMPGA) was done by Genci et al. [77]. Here the number of individuals among sub populations is distributed as different strategies, which becomes successful during the course of evolution. Malrey [78] has discussed about the distributed autonomous robots (agents) systems which necessitates the robot to have both learning and evolution ability to adapt in dynamic environment. Ghorbani et al. [79] have proposed a method of global path planning based on genetic algorithm to reach an optimum path for a mobile robot with obstacle avoidance. By using one-dimensional coding instead of the two-dimensional coding of the path via-points, complexity could be decreased and the fitness of both of the collision avoidance path and the shortest distance are integrated into a fitness function.
Moreno et al. [80] have presented an ultrasonic sensor localization system for autonomous mobile robot navigation in an indoor semi-structured environment.

Halal et al. [81] have described three cases of GA which have different chromosome attitudes, structures and objective functions (fitness). These attitudes define the robot's basic behaviour and fitness teaches the robot to determine its best path with respect to time and distance.

GA fuzzy logic controller (FLC) for path following of a four-wheel differentially skid steer mobile robot was presented and the fuzzy velocity and fuzzy torque was compared with the classical controller by Nazari et al. [82]. Latinovic et al. [83] have provided an improved set of rules governing the actions and behaviour of a simple navigating and obstacle avoiding mobile robot using Genetic Fuzzy Algorithm. Possibility of using FUZZY logic, IF-THEN rules, and Genetic Algorithm for autonomous mobile robot control is presented by Narvydas et al. [84].

Farshchi et al. [85] have presented a new algorithm for a mobile robot's global path planning using GA and fuzzy Algorithms. A genetic algorithm is used to find the optimal path for a mobile robot to move in a dynamic environment expressed by a map with nodes and links.

2.9 Conclusion

The literature relating to design and fabrication of mobile manipulator has been studied and briefly explained. This chapter provides a detailed review of literature related to robotic arm or manipulator and mobile platform or robots. The kinematic analysis of both the mobile robot and the robotic arm has been addressed separately and problems regarding posture regulation, trajectory tracking, path following etc. are also stated. Various models on skid steer principle have been elucidated; along with this a brief description of navigational techniques like fuzzy logic controller and genetic algorithms has also been given.

This thesis presents a unique robotic system which incorporates some of the details described in the previous few pages. The manipulator has an open design and is driven by a chain and sprocket mechanism as described in [13] & [14], similarly the suspension system of the mobile platform is inspired from Reimer's [29] and Bickler's [30] design which helps in equally distributing the load to all the wheels, irrespective of its position. The mobile platform has four standard wheels which are individually powered and works on the principle of skid steer mechanism described in section 2.6. Also, a rudimentary approach in automating the robot using basic Arduino codes based on logics derived from the artificial intelligence techniques highlighted in section 2.8 has been presented in this thesis.

DESIGN SPECIFICATION

Chapter 3

DESIGN SPECIFICATIONS

Preparing a design specification is one of the most primary tasks involved in the design process. This document intends to show what one is trying to achieve and not what one will finally end up with. Practically it is a set of clear cut requirements or critical parameters that helps in answering the problem at hand. For a design to be successfully implemented, it has to adhere to these important characteristics of the design specifications. As the work progresses we get to understand the project better and new information and knowledge gathered from the work lead to improvisation of the initial parameters and as a result the design specification constantly get evolved. Thus this documentation gives a detailed description of what is the intended task with the product and how it can be achieved.

This chapter has been divided into two separate sections, one dealing with the design specification of the robotic manipulator and the other dealing with the design specification of the mobile robotic platform.

A simple search for a robot design leads to a wide collection of information on the internet or in the market and to decide from this is a tedious task. The design requirements for both the manipulator and mobile platform have been extensively studied through literature survey and product survey. The study of design principles behind numerous robots available in the market and in the laboratories led to a precise understanding of our requirement.

3.1 Design Specifications of the Robotic Manipulator

A robotic manipulator is basically a chain of rigid bodies called *links* interconnected to one another by *joints*. The chain of links has an end-effector attached to it on one end and the other end is fixed to the base. The objective of the manipulator is to handle objects by controlling both the position and orientation of the end-effector by following a planned trajectory within its workspace as programmed.

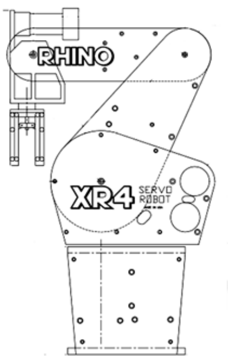


Fig. 3.1 Rhino XR4 [14]

The inspiration for the design of the robotic manipulator has been drawn from two highly recommended and well tested designs, the Rhino XR4 (*Fig.3.1*) and the Microbot Alpha II. Both are five-axis articulated robotic manipulators with tool pitch and roll motions. They use closed-loop position control with DC motors and incremental encoder for joint actuation. They are electric driven and has point-to-point motion control. The physical structure of these robots is such that the base motor is fixed vertically and the motors for the motion of the shoulder joint, elbow joint and tool pitch fixed horizontally onto the body and this body is then fixed on to a base motor. Also, the end effector's roll motion and the gripper mechanism are separately powered by smaller drives mounted at the end effector itself. These joints are actuated through chain and sprocket mechanism.

3.1.1 Fundamental Design of the Robotic Manipulator

The manipulator is powered by DC motors fixed at the body. This distributes the weight effectively and also helps in reducing the load on motors considerably unlike in designs with the motor fixed at the joints. The body is fixed on to a vertically placed motor at the base (Fig.3.2 b). In between the body and the end effector there are two links, these links are interconnected by joints at the shoulder and the elbow (Fig.3.2 c & d). These links are actuated through chain and sprocket mechanism. The end effector's pitch motion (Fig.3.2 e) is also controlled by a drive at the body. Two separate servo motors fixed on the end-effector actuate its roll motion (Fig.3.2 f) and the gripping mechanism. This enables the quick replacement of the end effector as a whole whenever necessary, making the robot a more versatile one. Similarly, the whole manipulator also could be easily detached from the body.

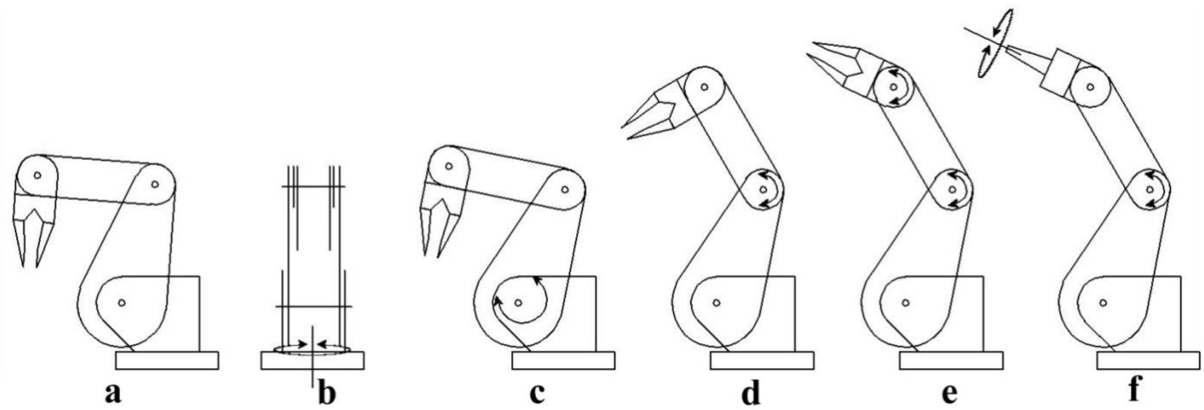


Fig.3.2 Various Motions of the Manipulator Parts

The basic dimensions of the manipulator are as shown in *Fig.3.3*. The shoulder joint is about 95mm from the base. The two links in between the end-effector and the body is about 170mm each. The length of the end-effector from the joint to the tip of the gripper is 135mm.

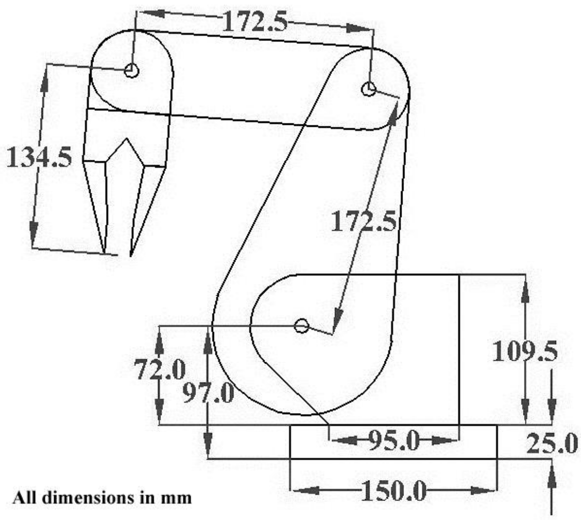


Fig.3.3 Basic Dimensions of the Manipulator

The rotational limitation of each link is illustrated in *Fig.3.4*. The shoulder joint link 1 can rotate a total of 120 degrees back and forth. Similarly link 2 can rotate a total of 220 degrees back and forth and the end-effector can rotate 180 degrees about its joint. The body attached to the vertically mounted motor rotates the manipulator perpendicularly through an angle of 340 degrees.

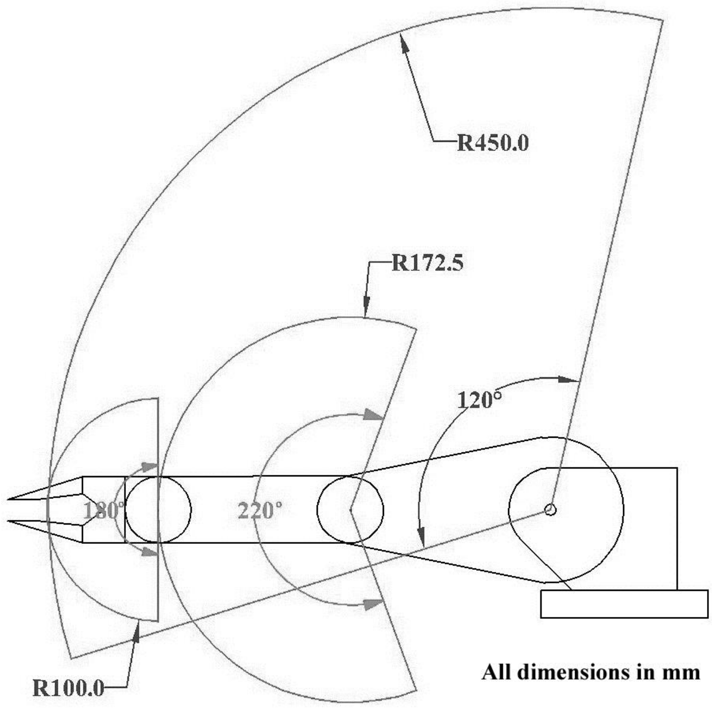


Fig.3.4 Rotation Angle for Each Link

3.2 Kinematics of Robotic Manipulator

Kinematic analysis deals with the analytical study of geometry of motion of mechanism with respect to a fixed reference co-ordinate system and without regard to the forces or moments that cause the motion. The study of kinematics of the manipulator helps us to understand the relationship between the position and orientation of the end-effector and the joint variables.

Kinematics of the manipulator deals with each moveable part of the robot by assigning it a frame of reference. Control of both position and orientation of the end effector is the primary objective.

Using Denavit-Hartenberg (DH) convention, coordinate frames for the manipulator are assigned as shown in the *Fig.3.5*.

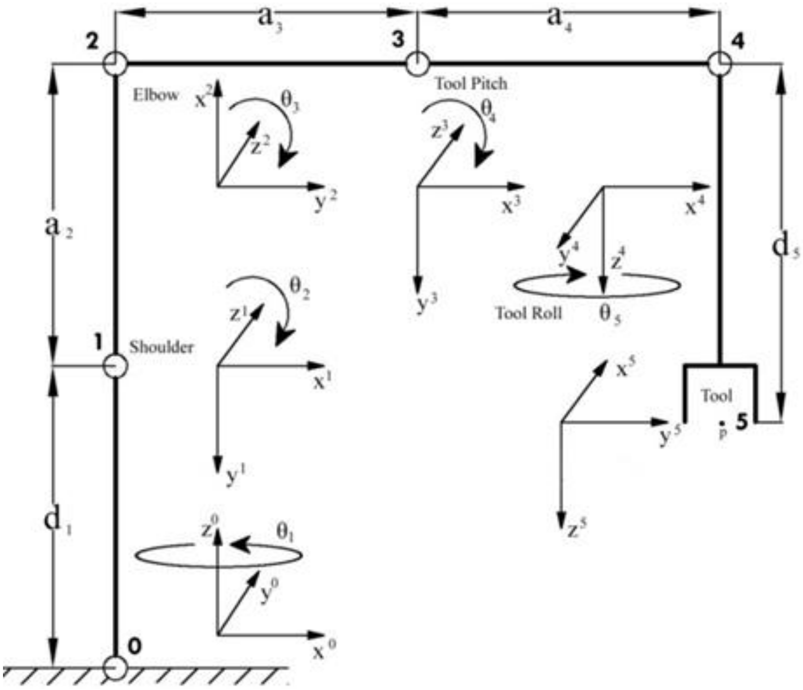


Fig.3.5 Link Coordinate Frame of the Manipulator

The position and orientation of the end-effector in terms of given joint angles is calculated using a set of equations and this is forward kinematics. This set of equations is formed using DH parameters obtained from the link coordinate frame assignation. The parameters for the manipulator are listed in *Table 1*, where θ_i is the rotation about the Z-axis, α_i rotation about the X-axis, d_i transition along the Z-axis, and a_i transition along the X-axis.

Table 3.1 Kinematic Parameters of the Manipulator

Axis	*Θ*	*d(mm)*	*a(mm)*	*α*
1	θ_1	$d_1 = 95$	0	$-\pi/2$
2	θ_2	0	$a_2 = 170$	0
3	θ_3	0	$a_3 = 170$	0
4	θ_4	0	$a_4 = 25$	$-\pi/2$
5	θ_5	$d_5 = 135$	0	0

The set of link coordinates assigned using DH convention is then transformed from coordinate frame (k_i) to (k_{i-1}), where k is the joints, using a homogeneous coordinate transformation matrix given in Eq.3.2.1

$$A_i = Rot(z,\theta_i)Trans(0,0,d_i)Trans(a_i,0,0)Rot(x,\alpha_i) = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i)\cos(\alpha_i) & \sin(\theta_i)\sin(\alpha_i) & \alpha_i\cos(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i)\cos(\alpha_i) & -\cos(\theta_i)\sin(\alpha_i) & \alpha_i\sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.2.1)$$

On substituting the DH parameters in *Table 1* into eq. 3.2.1, we get individual transformation matrices T_0^1 to T_4^5, and a global matrix of transformation T_0^5 as in eq. (3.2.2):

$$\mathrm{T}_0^5=\mathrm{T}_0^1\mathrm{T}_1^2\mathrm{T}_2^3\mathrm{T}_3^4\mathrm{T}_4^5 = \begin{bmatrix} m_x & n_x & o_x & p_x \\ m_y & n_y & o_y & p_y \\ m_z & n_z & o_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.2.2)$$

where ($\mathrm{p}_x, \mathrm{p}_y, \mathrm{p}_z$) represent the position and ({m_x,m_y, m_z}, {$\mathrm{n}_x, \mathrm{n}_y, \mathrm{n}_z$}, {$\mathrm{o}_x, \mathrm{o}_y, \mathrm{o}_z$}) the orientation of the end-effector given by the eqs.(3.2.3) to (3.2.14).

$$\mathrm{m}_x = \mathrm{C}_1\mathrm{C}_{234}\mathrm{C}_5 + \mathrm{S}_1\mathrm{S}_5 \quad (3.2.3)$$

$$\mathrm{m}_y = \mathrm{S}_1\mathrm{C}_{234}\mathrm{C}_5 - \mathrm{C}_1\mathrm{S}_5 \quad (3.2.4)$$

$$\mathrm{m}_z = -\mathrm{S}_{234}\mathrm{C}_5 \quad (3.2.5)$$

$$\mathrm{n}_x = -\mathrm{C}_1\mathrm{C}_{234}\mathrm{S}_5 + \mathrm{S}_1\mathrm{C}_5 \quad (3.2.6)$$

$$\mathrm{n}_y = -\mathrm{S}_1\mathrm{C}_{234}\mathrm{S}_5 - \mathrm{C}_1\mathrm{C}_5 \quad (3.2.7)$$

$$\mathrm{n}_z = \mathrm{S}_{234}\mathrm{S}_5 \quad (3.2.8)$$

$$\mathrm{o}_x = -\mathrm{C}_1\mathrm{S}_{234} \quad (3.2.9)$$

$$\mathrm{o}_y = -\mathrm{S}_1\mathrm{S}_{234} \quad (3.2.10)$$

$$\mathrm{o}_z = -\mathrm{C}_{234} \quad (3.2.11)$$

$$\mathrm{p}_x = \mathrm{C}_1(\mathrm{a}_2\mathrm{C}_2 + \mathrm{a}_3\mathrm{C}_{23} + \mathrm{a}_4\mathrm{C}_{234} - \mathrm{d}_5\mathrm{S}_{234}) \quad (3.2.12)$$

$$\mathrm{p}_y = \mathrm{S}_1(\mathrm{a}_2\mathrm{C}_2 + \mathrm{a}_3\mathrm{C}_{23} + \mathrm{a}_4\mathrm{C}_{234} - \mathrm{d}_5\mathrm{S}_{234}) \quad (3.2.13)$$

$$\mathrm{p}_z = \mathrm{d}_1 - \mathrm{a}_2\mathrm{S}_2 - \mathrm{a}_3\mathrm{S}_{23} - \mathrm{a}_4\mathrm{S}_{234} - \mathrm{d}_5\mathrm{C}_{234} \quad (3.2.14)$$

Here C_i=cos(θ_i), S_i=sin(θ_i), C_{ij}=cos($\theta_i + \theta_j$), S_{ij}=sin($\theta_i + \theta_j$), C_{ijl}=cos($\theta_i + \theta_j + \theta_l$), S_{ijl}=sin($\theta_i + \theta_j + \theta_l$).

From this transformation matrix, using MATLAB the position (translation) of end-effector with reference to base frame as a function of the joint angles is depicted in *Fig. 3.6&3.7*.

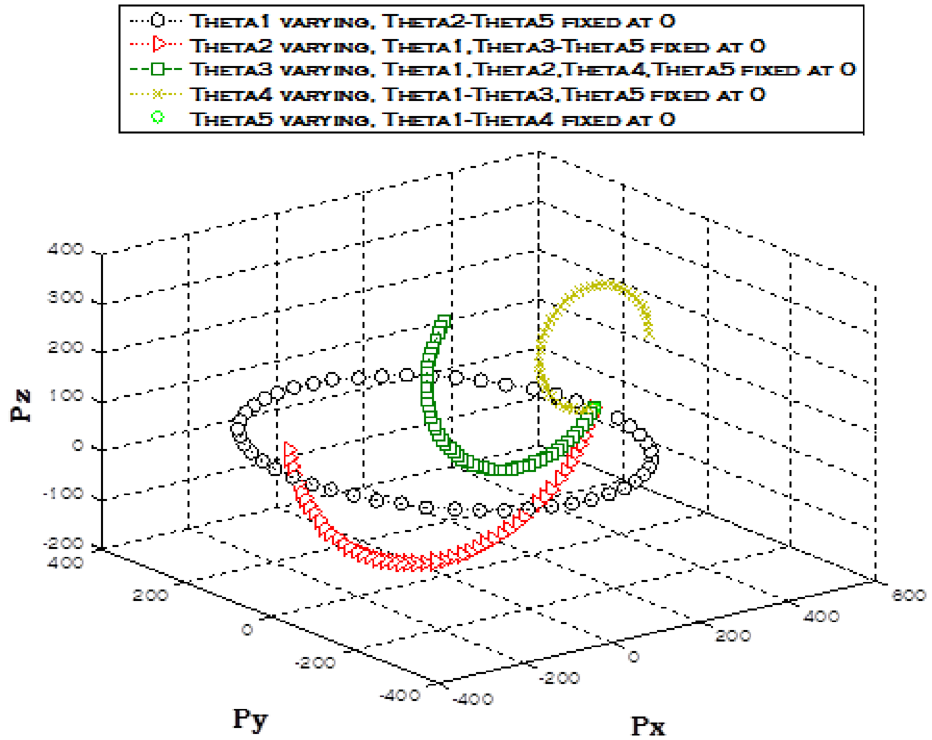


Fig.3.6 Variation of End-Effector Position Vector when one Joint Angle is varied while others are Zero.

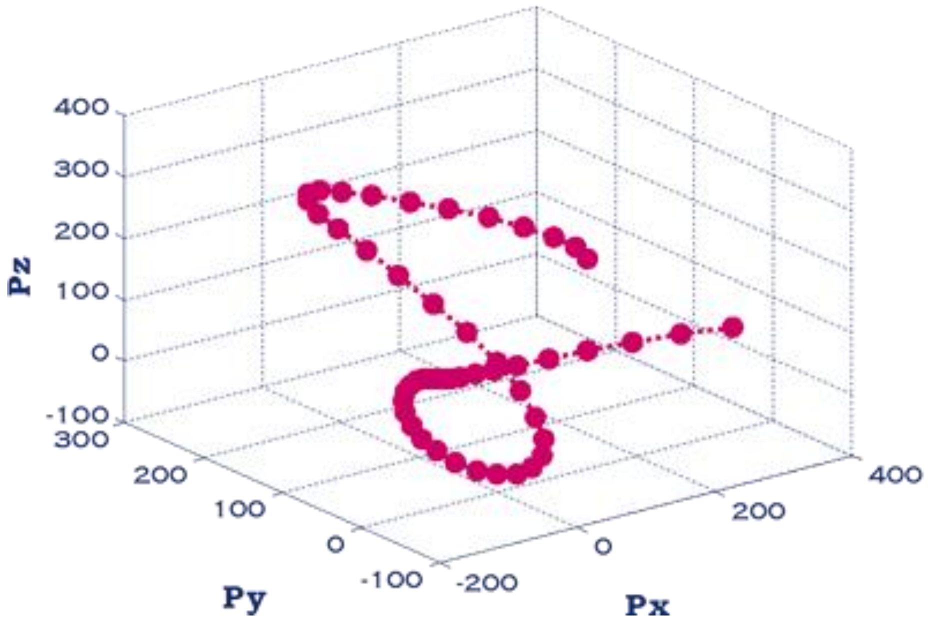


Fig.3.7 Variation of End-Effector Position Vector when all Joint Angles are varied uniformly and simultaneously.

With the kinematic of the robotic manipulator established, the workspace of the manipulator is defined. The front view (*Fig. 3.8a*), side view (*Fig. 3.8b*) and the top view (*Fig. 3.8c*) of the work envelop is shown below. From the figure we can deduce that the maximum reach of the manipulator from the centre of its body is 550mm. And the length of the manipulator from the shoulder joint is 500mm.

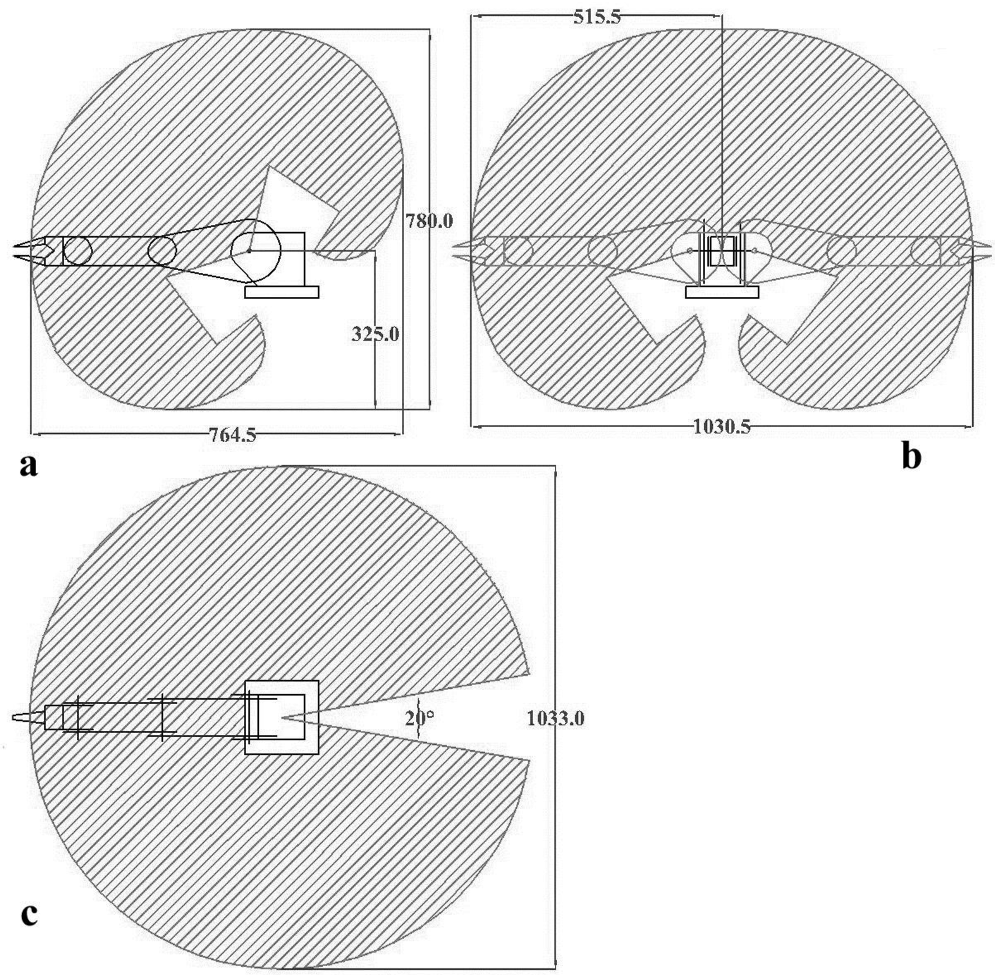


Fig. 3.8 The Workspace of the Manipulator

3.3 Drive Mechanism for the Robotic Manipulator

The manipulator uses electric powered DC motors and servo motors for actuation. As mentioned earlier all the motors are fixed on to the body and hence to transfer the power we use a set of mechanical power trains and in this case chains and sprockets.

Four 10 RPM Side Shaft Super Heavy Duty DC Gear Motors from Nex-Robotics are used to drive the shoulder joint, elbow joint, pitch motion of the end-effector and the rotation of the body. This motor has a sturdy built with large gears which can handle the stall torque produced by the motor. It operates between 4V to 12V, giving 10 RPM at 12V. The motor shaft is 8mm in diameter and is 19mm long; also it has a D shaped cross section which facilitates better coupling.

Two RC Servo Motors of maximum 4kg-cm-force torque and a rotating angle of +/-180 degrees is used to drive the gripper mechanism and the roll of the end-effector. These high performance motors have inbuilt motor, gearbox, controller and position feedback and can be easily controlled using simple pulse controller. The operating voltage of the motor is between 4V-6V with 4kg-cm-force torque given at 6V. The speed of the motor is 60 degrees in 0.15sec. The gripper can hold a maximum of 500gms using this motor.

According to the American National Standards Institute (ANSI) standards B29.1for *Precision Power Transmission Roller Chains, Attachments, and Sprockets* (*Appendix A*), we can arrive at a selection of chain depending on the working load. The chains with minimum stated working load is for 64kg and below. As our work deals with loads less than 64kg we can consider chain type 25 which has a pitch length of 6.35mm, roller diameter of 3.30mm, width of 3.175mm and tensile strength of 354kg. A brief illustration of the same is given below in *Fig.3.9*.

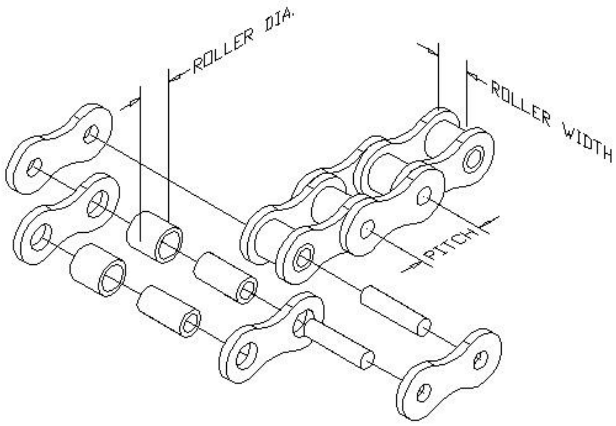
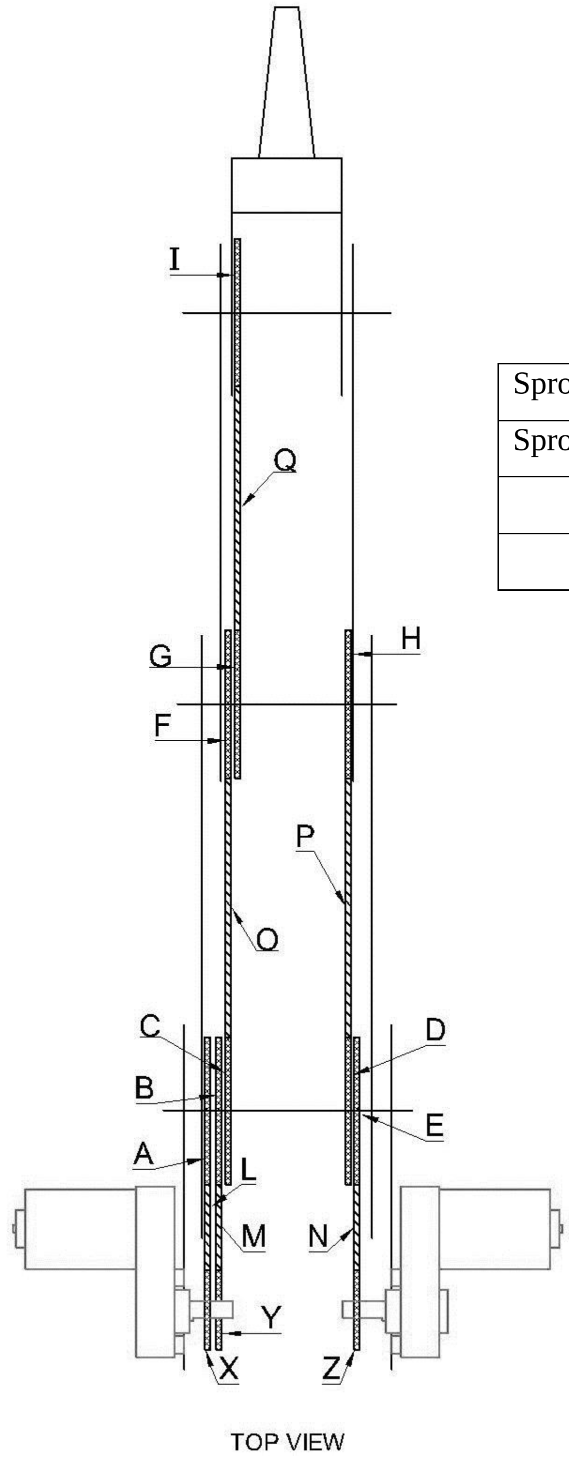


Fig.3.9 Chain Parameters

Chain type 25 is commonly used inside motor bike engines for power transmission. Similarly, in motorbike engines sprockets with 14 and 28 numbers of teeth are used in combination with this chain type. As this model is built with readily available parts these components were chosen to fabricate the transmission system for the manipulator.

The mechanical power train for the robotic manipulator is as shown in Fig.3.10. Here A, B, C, D, E, F, G, H and I are sprockets of Type 1 with 28 teeth and X, Y and Z are sprockets of Type 2 with 14 teeth coupled with i, ii and iii motors respectively. L, M. N, O, P and Q are the chains used to pair the sprockets. X coupled to the motor i transfers the motor's power to A through chain L and A actuates the shoulder joint of the manipulator. Y transfers the power from motor iii to B via chain M, and C coupled to B drives F by means of chain O. F is coupled to G which in turn drives I through chain Q to actuate the pitch motion of the end-effector. The power from motor iii is transferred by Z coupled to it. E is driven by Z with the help of chain N. D coupled to E drives H via chain P which actuates the elbow joint.

Sprocket Type 1	A, B, C, D, E, F, G, H, I
Sprocket Type 2	X, Y, Z
Chains	L, M, N, O, P, Q
Motors	i, ii, iii



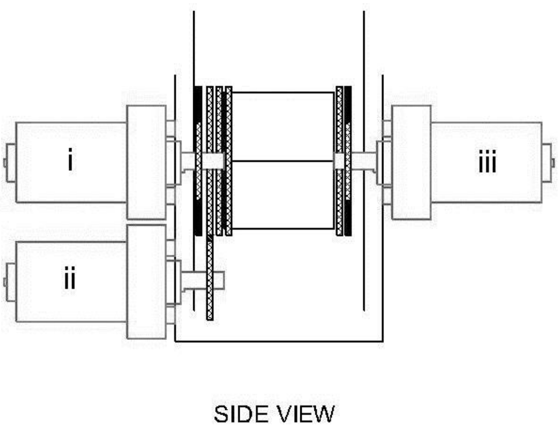


Fig.3.10 Chain & Sprocket Power Train of the Manipulator

We can determine the speed ratio of the sprocket and chain mechanism by using the following formula:

$$\text{Speed Ratio} = \frac{N_1}{N_2} \qquad (3.3.1)$$

where, N_1 is the driver sprocket and N_2 is the driven sprocket.

Here the driver sprocket is the Type 2 sprocket with 14 teeth and driven is Type 1 with 28 teeth, substituting in Eq.3.3.1

$$\frac{14}{28} = 0.5$$

Therefore, the ratio between Sprocket Type 1 and 2 is 0.5.

The following formula gives the pitch diameter of the sprocket.

$$Pitch\ Diameter = \frac{P}{\sin\frac{180}{N}} \tag{3.3.2}$$

where, P is the pitch of the roller chain and N is the number of teeth on the sprocket.

We use a roller chain with pitch 6.35mm and sprockets Type 1 and Type 2 has 28 and 14 teeth respectively. Substituting these in Eq.(3.3.2)

$$\frac{6.35}{\sin\frac{180}{28}} = 56.71mm \text{ For Type 1 sprocket}$$

$$\frac{6.35}{\sin\frac{180}{14}} = 28.56mm \text{ For Type 2 sprocket}$$

Since two types of sprockets with different diameters are used, there is a change in speed while transferring the power. This change in speed can be calculated using the following equation.

$$Diameter_1 \times RPM_1 = Diameter_2 \times RPM_2 \tag{3.3.3}$$

where, $Diameter_1$ and $Diameter_2$ are the pitch diameter of sprockets and RPM_1 and RPM_2 are their respective speed.

Taking $Diameter_1 = 56.71mm$, $Diameter_2 = 28.56mm$ and $RPM_2 = 10rpm$ which is the speed of the motor coupled to sprocket Type 2, substituting in eq.(3.3.3)

$$56.71 \times RPM_1 = 28.56 \times 10$$

$$RPM_1 = \frac{28.56 \times 10}{56.71}$$

$$RPM_1 = 5.036rpm$$

Therefore, all sprocket of Type 1 will be rotating at a speed of 5rpm.

3.4 Design Specification of the Mobile Robotic Platform

A manipulator fixed to a position limits its working space and this is a fundamental disadvantage. On the contrary a mobile robot is more effective as it can move around in a wider workspace. This ability of mobile robot is exploited here in this work by implementing it with a manipulator.

Locomotion is the key aspect in mobile robots. As discussed earlier there are various types of locomotion mechanism in nature but the one considered here is the rolling motion, i.e. the wheel. Wheeled mobile robots are the most widely used robots for mobile navigation. The locomotion mechanism of a mobile robot deals with the mobile robot's stability, manoeuvrability, controllability, contact characteristic and type of environment through which the robot navigates.

Fig.3.11 a. CoroWare Robotics: Explorer; b. NASA Mars Rover: Pathfinder

The current design incorporated a four wheeled mobile robot with all wheels fixed and non-steerable. Each wheel is powered individually and works on the principle of skid steer. The following work has been inspired from the two well established patented designs by W. E. Reimer [29] and D. B. Bickler [30]. CoroWare Robotics had implemented Reimer's design in their Explorer Robot (*Fig.3.11a*) and NASA had implemented Bickler's design in their current Mars Rovers (*Fig.3.11b*). These designs employ unique suspension system which enables them to traverse irregular surface. Bickler's design implements a rocker-bogie mechanism with six wheels while Reimer's design uses four wheels. Reimer's design is commonly used in heavy machineries like bulldozers, road-rollers, etc.

3.4.1 Fundamental Design of the Mobile Robotic Platform

The mobile platform has four fixed wheels powered by four high torque DC motors and works on the principle of skid-steer. A novel suspension system facilitates the mobile robot to travel over uneven or rough terrain (*Fig.3.12a*). This suspension system assists the robot to distribute the loads equally to all wheels to a greater extend by providing the wheels a relative vertical movement. Also, the lateral tilting of the robot onto a wheel while going over uneven surface can be reduced substantially (*Fig.3.12b*). Unlike in common four wheeled vehicle this mobile base has only one axel. This axel is centrally located and has two rocking frames at either end of it. The front and back wheel on one side of the mobile base is fixed on to one rocking frame. A cross beam is connected to the two rocking frames with help of two connecting rods, thus limiting the motion of the frames. Thus these frames give the wheels the relative vertical movement about the central axel.

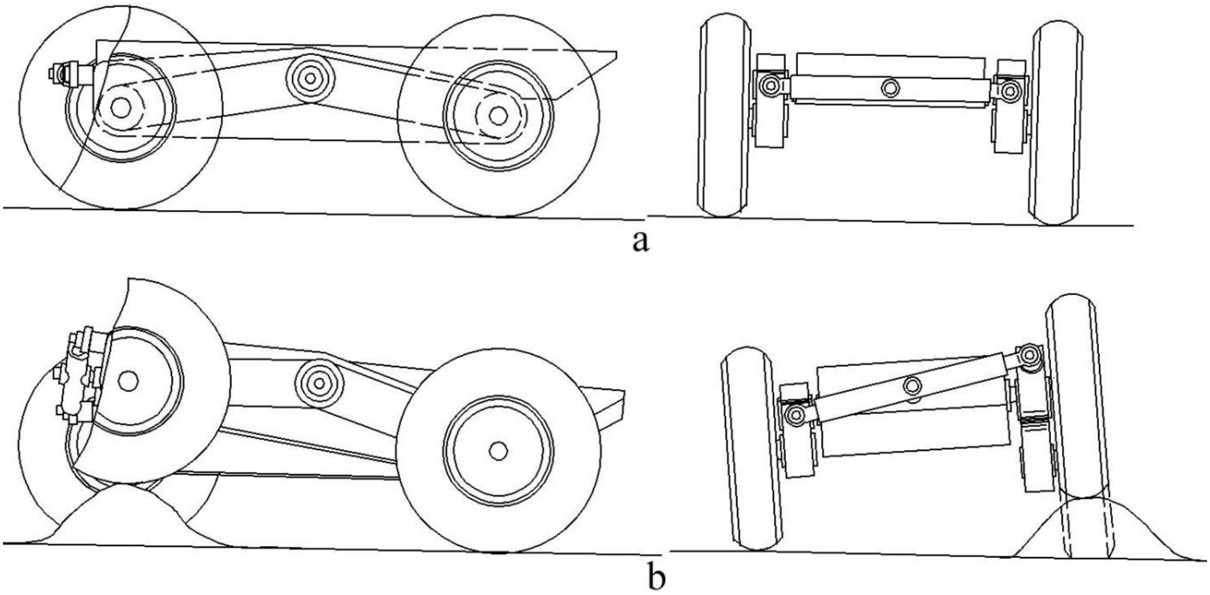


Fig.3.12 Reimer's Suspension Design [29]

The basic diemension of the mobile platform is as shown in *Fig.3.13*. The wheel base of the platform is 500mm and the track width is 420mm. Four 110mm diameter wheels are used in this model. The approximate height of the platform from the ground level is 175mm.

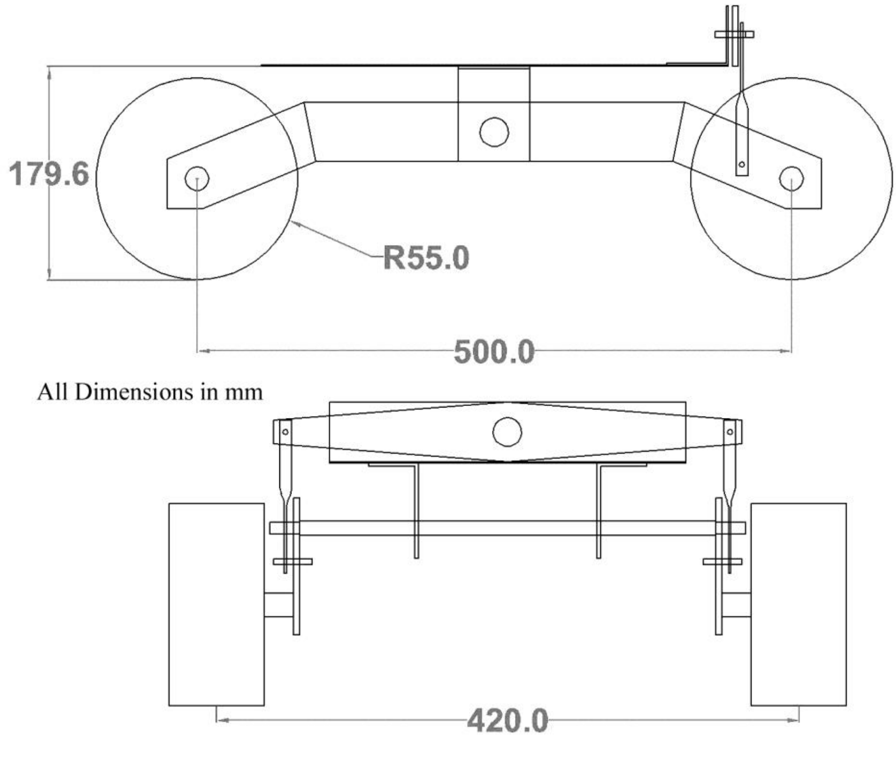


Fig.3.13 Basic Dimensions of the Mobile Robotic Platform

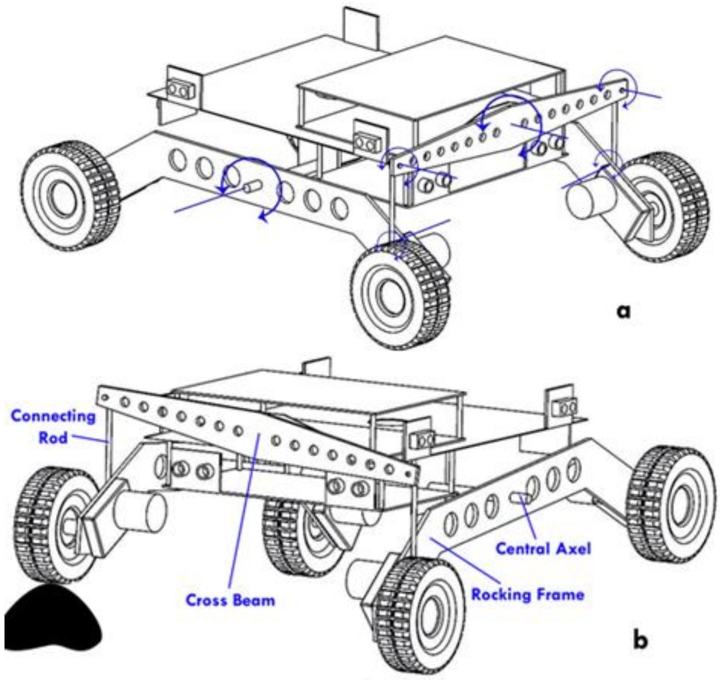


Fig.3.14 Mechanism of the Mobile Platform

(Fig.3.14a) gives a clear idea of the suspension mechanism of the mobile platform and *(Fig.3.14b)* shows how the suspension works when the mobile platform traverses uneven surfaces.

3.5 Kinematic Analysis of the Mobile Robotic Platform

A skid steer mechanism is implemented in this mobile robot. The basic principle of skid steer mechanism is similar to differential drive where the velocity difference between two wheels drives the robot in any required path and direction. The main advantages of this mechanism are: no steering mechanism needed, better traction, best suited for rough terrains.

No slippage and single point tread contact, are the assumptions made while using differential drive to control a pair of rolling wheels. Though this assumption is usually adequate for differential wheels with relatively small contact area, in skid-steered vehicles with larger area of wheel contact we cannot assume that.

The Y axis of the local frame should be aligned towards the forward motion and the origin should be centered within the left and right contact surfaces on the plane. Two control inputs govern the skid-steered mechanism: the linear velocity of the left and right treads. The direct kinematics can be stated as follows:

$$\begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} = f_d \begin{bmatrix} V_l \\ V_r \end{bmatrix} \tag{3.5.1}$$

With respect to the vehicles local frame $v = (v_x, v_y)$is its translational velocity and $\omega_z$is its angular velocity.

Unlike in typical platforms having single instantaneous centre of rotation (ICR), a skid steer platform has three. One for the vehicle $ICR_v = (x_{ICR_v}, y_{ICR_v})$ and one each for both the right tread $ICR_r = (x_{ICR_r}, y_{ICR_r})$ and left tread $ICR_l = (x_{ICR_l}, y_{ICR_l})$ as shown in *Fig.3.15*.

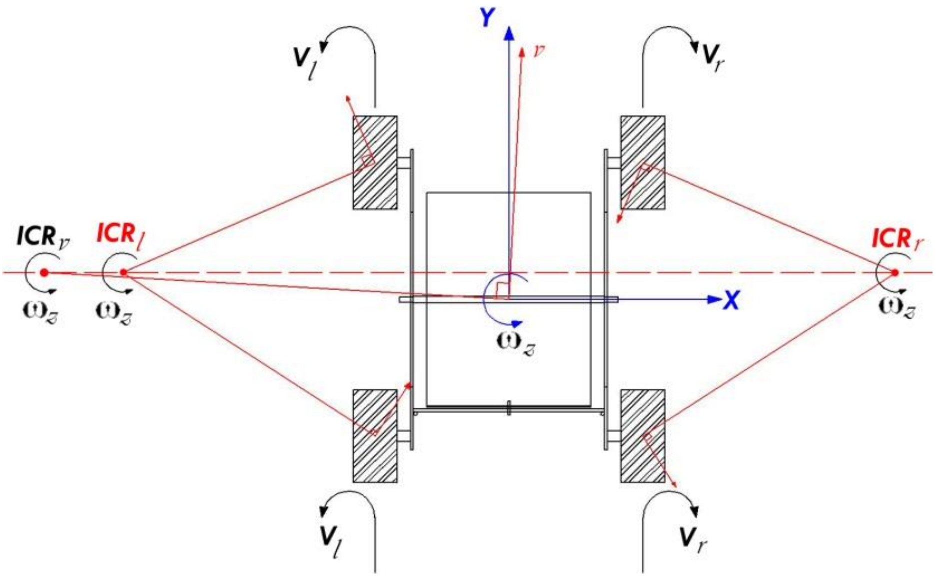


Fig.3.15 Vehicle and tread ICRs on the plane

Therefore, the geometrical relationship between the vehicle's rotational and translational velocities and the ICR positions are as follows:

$$x_{ICR_v} = \frac{-v_y}{\omega_z} \tag{3.5.2}$$

$$x_{ICR_l} = \frac{\alpha_l \, . \, V_l - v_y}{\omega_z} \tag{3.5.3}$$

$$x_{ICR_r} = \frac{\alpha_r \, .V_r - v_y}{\omega_z} \tag{3.5.4}$$

$$y_{ICR_v} = y_{ICR_l} = y_{ICR_r} = \frac{v_x}{\omega_z} \tag{3.5.5}$$

where (α_l, α_r) are the correction factors that affect the tread speeds because of mechanical issues such as tire inflation condition, tension of transmission belt, etc.

From Eqs. (3.5.2) – (3.5.5) the modified kinetic relation (3.5.1) reflecting the ICR equations is:

$$\begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} = A \, . \begin{bmatrix} V_l \\ V_r \end{bmatrix} \tag{3.6.6}$$

where A = $\frac{1}{x_{ICR_r} - x_{ICR_l}} \begin{bmatrix} -y_{ICR_v} \, . \, \alpha_l & y_{ICR_v} \, . \, \alpha_r \\ x_{ICR_l} \, . \, \alpha_l & -x_{ICR_r} \, . \, \alpha_r \\ -\alpha_l & \alpha_r \end{bmatrix}$

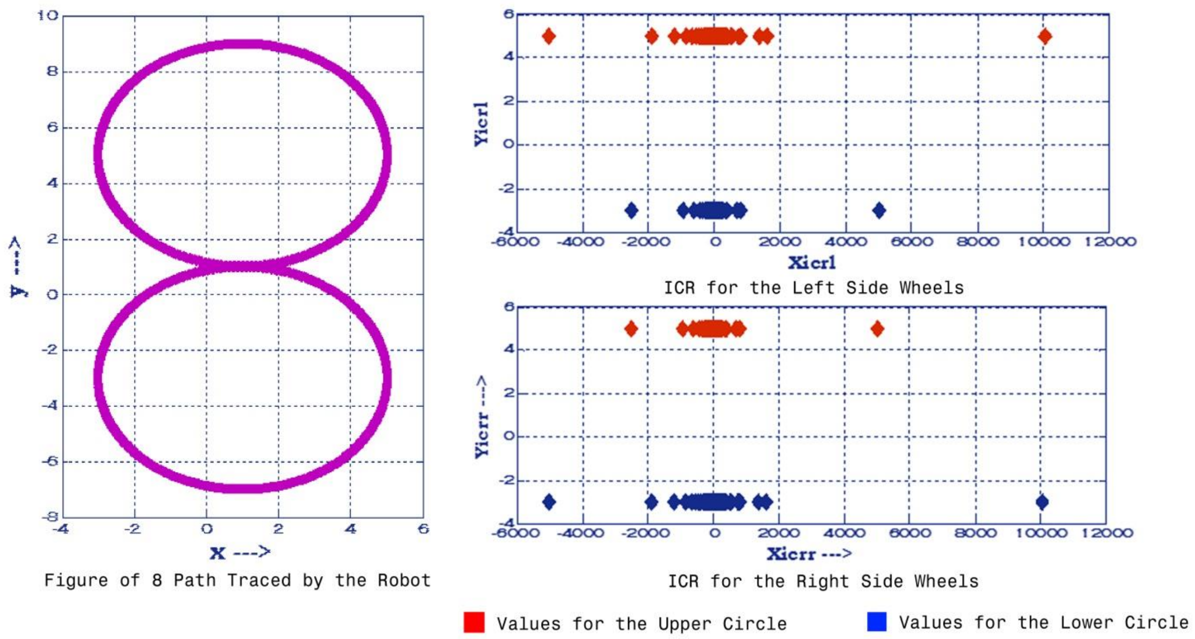


Fig.3.16 The Path Traced by the Robot and the Corresponding ICR Values

Using MATLAB a program was created to find the ICR_r and ICR_l for a know $ICR_v$and$v$. The program was executed to trace a figure of 8 paths by forming two side by side circles. The corresponding values for ICR_r and ICR_l is shown in *Fig.3.16*. The red dots are associated with the upper circle and blue with the lower circle.

3.6 Drive Mechanism for the Mobile Robotic Platform

The mobile platform is fitted with four electric powered DC motors for the purpose of navigation. All the four motors are bolted on to the frame and directly coupled with the four fixed wheels of the mobile platform, thus simplifying the drive mechanism of the mobile robotic platform.

Like in the case of the robotic manipulator these four Side Shaft DC motors were also procured from Nex-Robotics. This DC motor has a speed of 30 RPM. These motors have metallic internal gears making them the right choice for heavy duty and high torque jobs. This motor operates with a voltage between 4V and 12V, giving the maximum speed of 30 RPM at 12V. The motor shaft is 8mm in diameter and is 19mm long; also it has a D shaped cross section which facilitates better coupling with the wheels.

3.7 Controller of the Mobile Manipulator

Arduino, an open source electronic prototyping platform is used as a controller in this project. It is a user friendly, simple to use, easy to program controller. With one Arduino we can realize different jobs and this makes it very flexible to use. An Arduino can be directly connected to a computer using an USB interface and programmed using the Arduino programming language (based on Wiring) and the Arduino development environment (based on Processing).

Arduino Mega 2560 is used in this project. This board incorporates an ATMega 2560 microcontroller. This board has 53 ports through which one can send signals to control various components of the mobile robotic manipulator.

3.8 Design Specification in Brief

Robotic Manipulator

Configuration	5 Axes plus gripper
	All axes completely independent
	All axes can be controlled simultaneously
Drives	Four DC motors with integral gearboxes and optical encoders
	Two programmable servo motors for controlling the gripper.
Controller	Arduino®, the AVR based microcontroller
Weight	5kg with motors and all electronic components
Gripper Payload	500gms
Reach	55cm from centre of shoulder axel at the body to the finger tip
Work Envelop	Motor A - Body Rotation - 340 degrees
	Motor B - Shoulder Rotation - 135 degrees
	Motor C - Elbow Rotation - 180 degrees
	Motor D - Wrist Rotation - 180 degrees
	Motor E - Gripper Rotation - -/+180 degrees
Gripper opening	50mm
End Effector Options	Gripper attachment or any other attachments like: drill, vacuum, etc.

Mobile Platform Specification

Configuration	4 fixed wheel
	All wheels independently powered and controlled
Drives	Four PMDC servo motors with integral gearboxes and optical encoders

Controller	Arduino®, the AVR based microcontroller
Payload	7-8kgs
Speed	0.250-0.280m/s with payload of 5kg
Weight	7kg with motors and all electronic components.
Dimensions	42cm is the track width
	50cm is the wheelbase
Other Details	Novel Suspension system
	Zero radius turn

3.9 Conclusion

The primary focus of this thesis is to design and prototype a robot that can traverse through rough terrain, climb inclinations over 25 degrees and compactly fit into a small space. This chapter presents the design specifications of the mobile manipulator. Various configurations are scrutinised and a design best suited is selected. The various parts that build up the mobile manipulator is individually studied and presented separately. This chapter is the basis on which the concept designs are generated.

CONCEPT DESIGN

Chapter 4

4.1 Concept Design of the Articulated Robotic Manipulator

4.2 Concept Design of the Mobile Robotic Platform

4.3 The Final Concept Design of the Mobile Robotic Manipulator

4.4 Conclusion

CONCEPT DESIGN

This chapter deals with the design and modelling of the mobile robotic manipulator. Initially few preliminary designs are created and from which one design or a combination of designs that best suits our requirement and specification is chosen. The decisions are made using the design specification as a guideline. The final design should not be very expensive to manufacture or quiet impossible to build on our own. We should be able to realize the design within a stipulated amount of time too.

While generating concept designs for this project, we have predominantly used design tools like CATIA and AutoCAD. These design tools were very useful in visualizing and understanding the basic ideas to be implemented. Using CATIA part modelling, each part of the robot was created separately. These parts were then assembled and virtually tested to see their kinematics and performance.

The dimensions stated in the design specification are considered while modelling. Various factors like functions intended with design, manufacturing ease, time limits, overall appearance of the final product, etc. were some of the key issues that played an important role in designing the robot.

The fundamental features of the final design used for manufacturing the robot have been presented here.

4.1 Concept Design of the Articulated Robotic Manipulator

The manipulator is basically made up of five parts or links. The five links are: the base, the body, arm link 1 (upper-arm), arm link 2 (forearm) and the end-effector housing (hand). The links are interconnected by joints creating 4 axes of rotation for the links thus making them articulated.The joint between the base and the body forms the body rotation, the joint between the body and the upper-arm creates the shoulder rotation, the joint between the upper-arm and forearm creates the elbow rotation and finally the joint between the forearm and hand creates the wrist rotation. Each of these links is built keeping the design specification in mind to meet the requirement. The materials for building the manipulator are chosen intelligently so that it caters to the function of the part.

The base (*Fig.4.1*) of the manipulator is a crucial part as it has to take the full load of the manipulator and it also has to attach the manipulator to the mobile platform. Therefore this part has to be really strong and sturdy. Hence the material for this part has to be strong enough so that it shouldn't deform under load and it should withstand all shocks and vibrations.

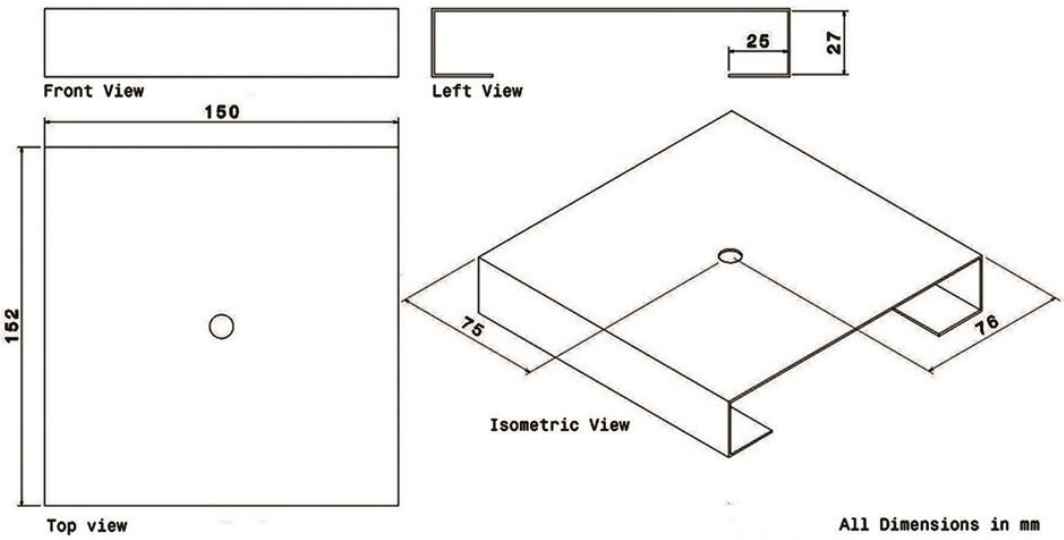


Fig.4.1 Base of the Robotic Manipulator

Like the base even the body (*Fig.4.2*) has to be very robust and strong since the body houses the three motors that drive the shoulder, elbow and the wrist joints.

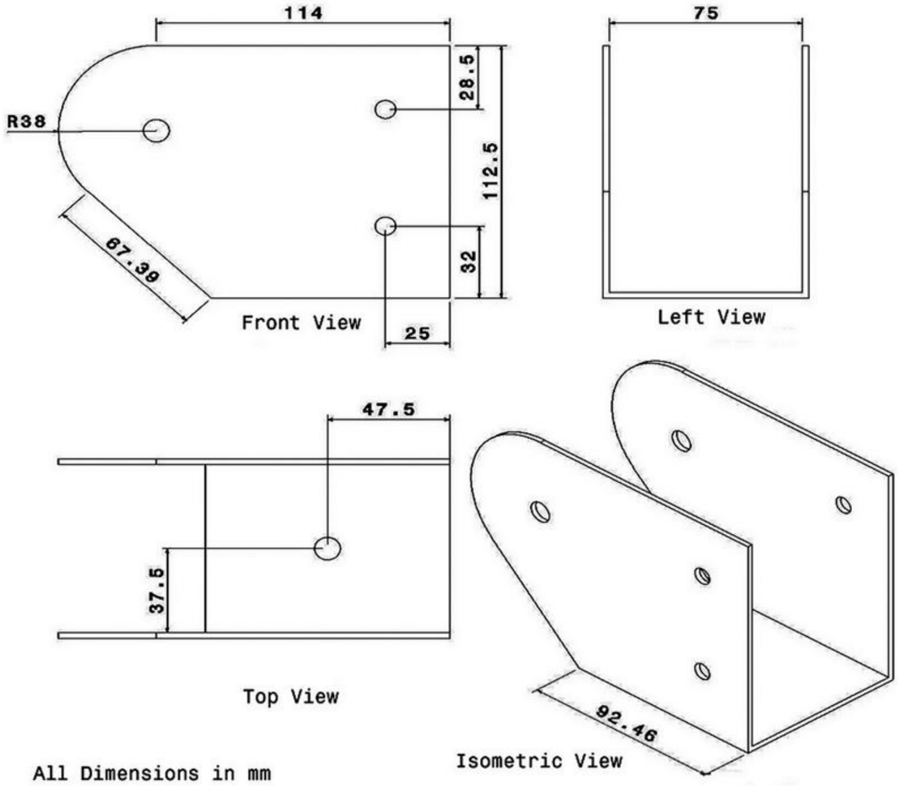


Fig.4.2 The Body of the Robotic Manipulator

The Arm Link 1 (upper-arm) (*Fig.4.3*) and Arm Link 2 (forearm) (*Fig.4.4*) are made of lighter materials than the base and the body. A 10mm axel is used to interconnect the upper-arm with the body and also to interconnect the upper-arm and the forearm.

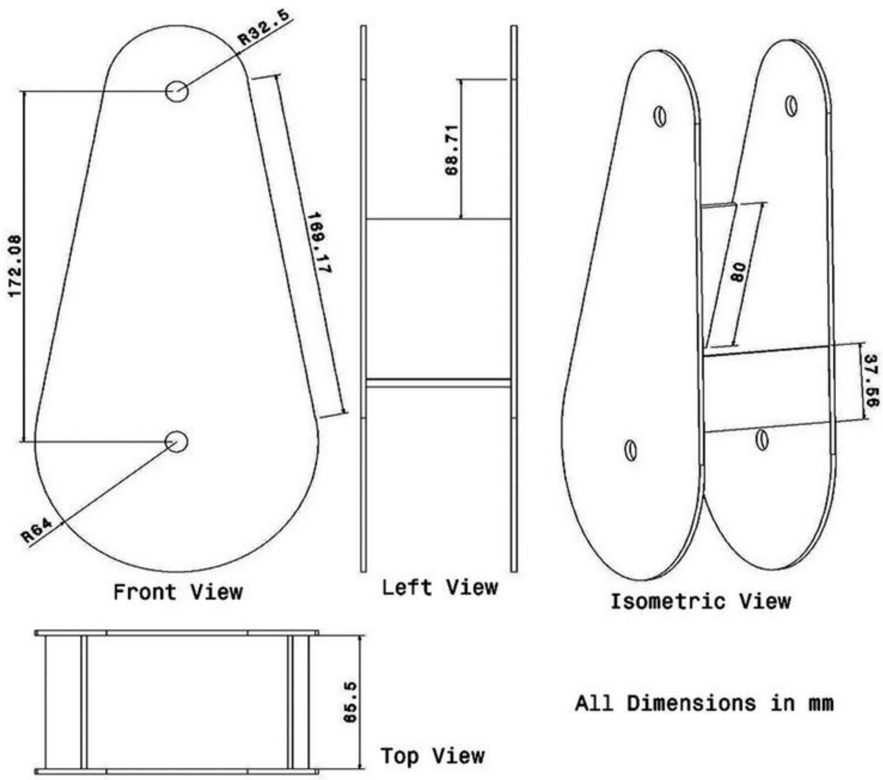


Fig.4.3 The Arm Link 1 (Upper-arm) of the Robotic Manipulator

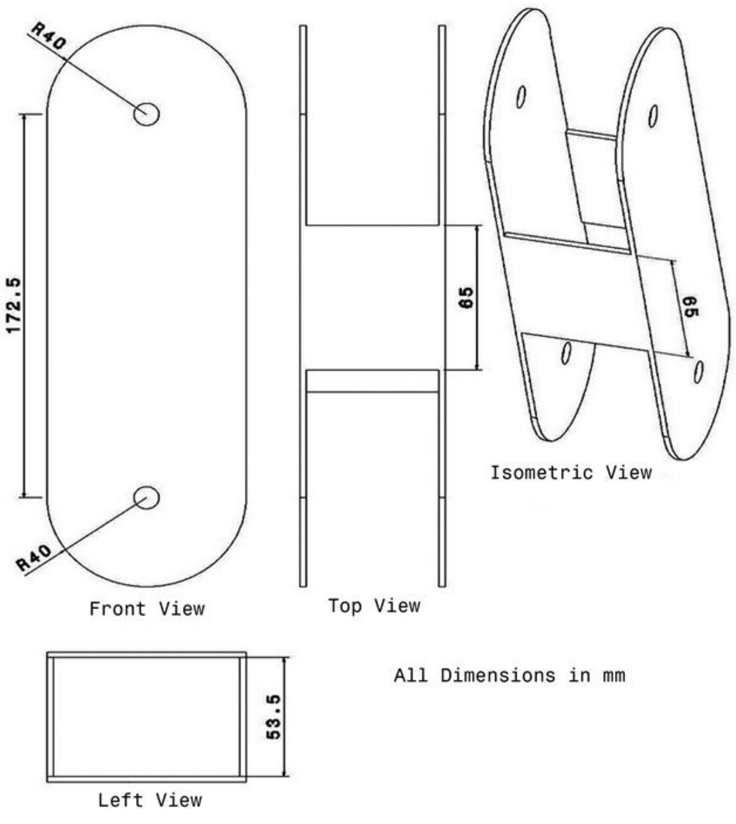


Fig.4.4 The Arm Link 2 (Forearm) of the Robotic Manipulator

The end-effector housing (hand) (*Fig. 4.5*) is the last link of the manipulator. The gripper or any other tool is secured on to this link. As in the case with the upper-arm and forearm, even the hand is also built with light materials.

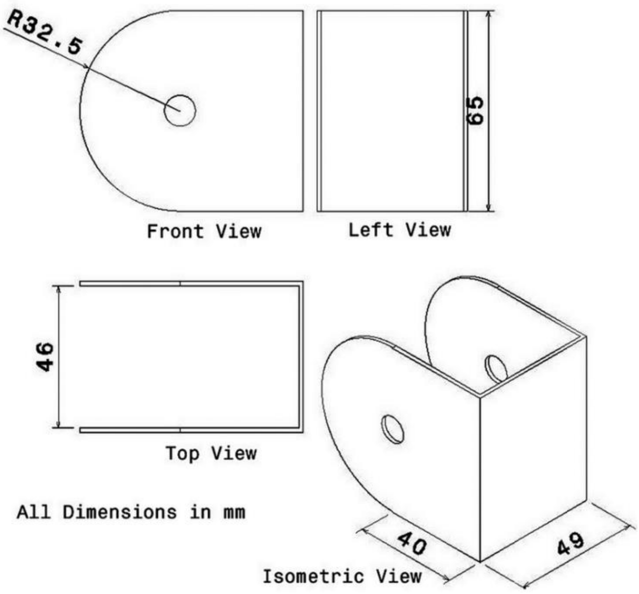


Fig.4.5 The End-effector Housing (Hand) of the Robotic Manipulator

Currently a gripper (*Fig.4.6*) is used as an end-effector. This gripper works on the principle of parallelogram mechanism, which gives the fingers a better gripping capability as they move parallel to each other. Presently the gripper can take a load of 500gms, but it can take heavier loads if a motor with higher torque is used for the clasping mechanism.

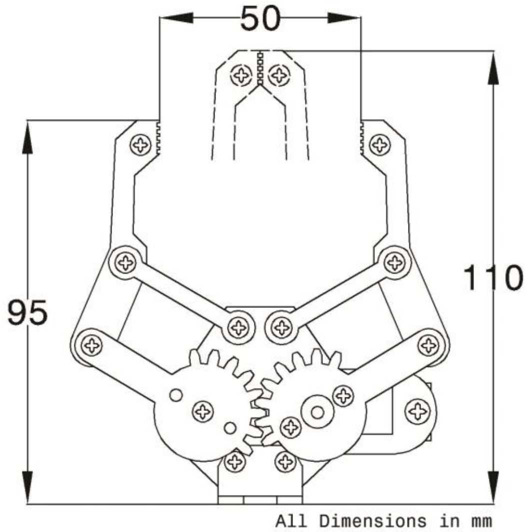


Fig.4.6 The Gripper with Parallelogram Mechanism

The drive mechanism (*Fig.4.7*) of the manipulator is as described in the specification. The various joints of the manipulator is rotated using a chain and sprocket mechanism powered by high torque motors.

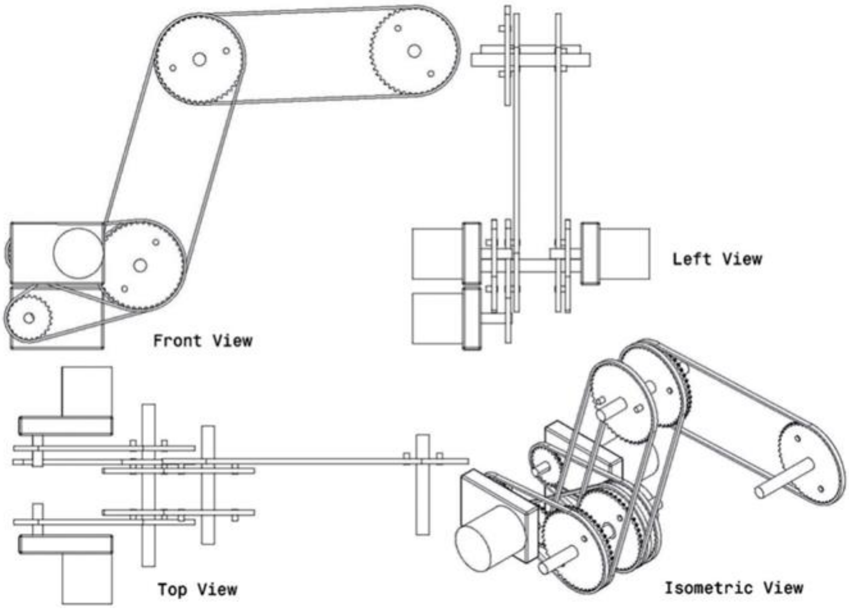


Fig.4.7 The Drive Mechanism of the Robotic Manipulator

All the parts described above will be finally assembled to build the 5 axes articulated robotic manipulator as shown in (*Fig.4.8*).

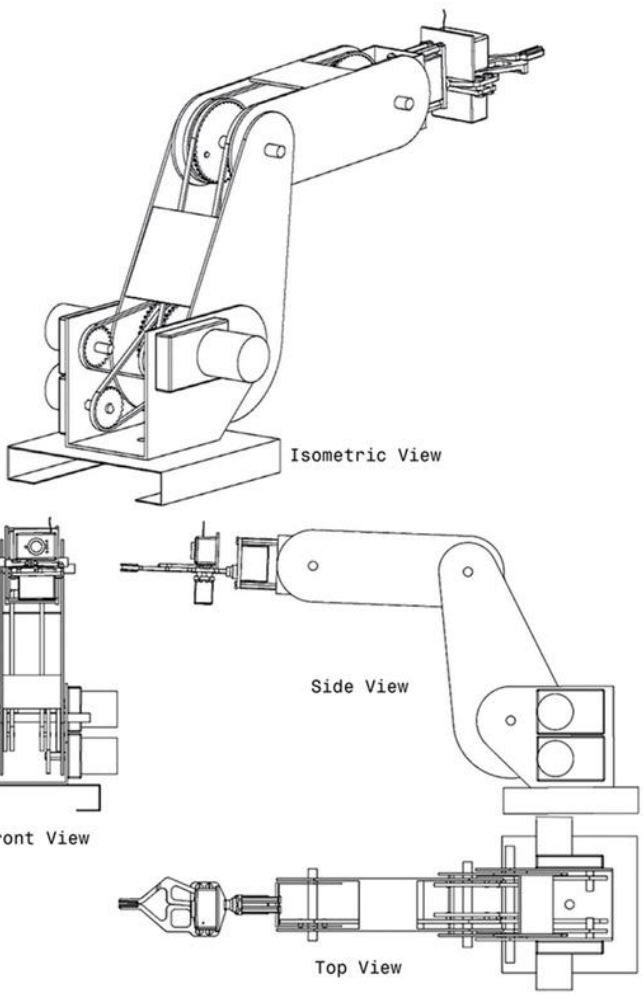


Fig.4.8 The fully assembled 5 Axes Articulated Robotic Manipulator

4.2 Concept Design of the Mobile Robotic Platform

The mobile platform has four fixed wheels and incorporates a novel suspension system (*Fig.4.9*). The front and the back wheels on one side is coupled with the motor and fixed onto the corresponding rocking frame. The two rocking frames are then fixed onto the centrally located axel. This facilitates the frames to rotate about that axel. Their rocking motion is limited by the cross frame connected to both the frames by a pair of connecting rods.

The materials for manufacturing the mobile platform were chosen keeping in mind that it has to endure tough terrains. With its unique suspension system and high power motors it is relatively easy for the robot to travel through uneven surfaces. As the robot is driven by skid steer mechanism it gives the robot added advantages like better traction, control and manoeuvrability.

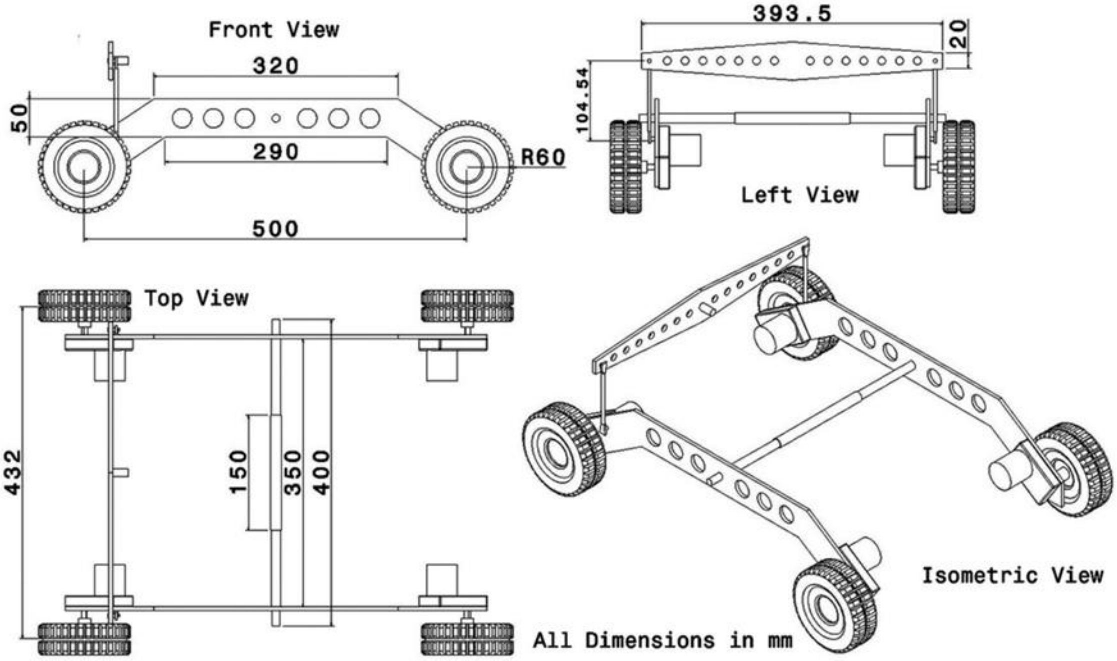


Fig.4.9 The Suspension of the Mobile Robot

The principle load on the mobile platform is the robotic manipulator and it is attached to the platform (*Fig.4.10*). This platform is also fitted to the central axel using a pair of ball-bearings and is pivoted on to the cross frame to control its tilt.

These parts are put together to make the mobile robot shown in (*Fig.4.11*). We can see how the mechanism enables it to travel over small obstacles by distributing the load relatively equally. This platform will not tip over due to the displaced centre of gravity acting on it because of the manipulator's out stretched arm even when travelling through tough and irregular terrains.

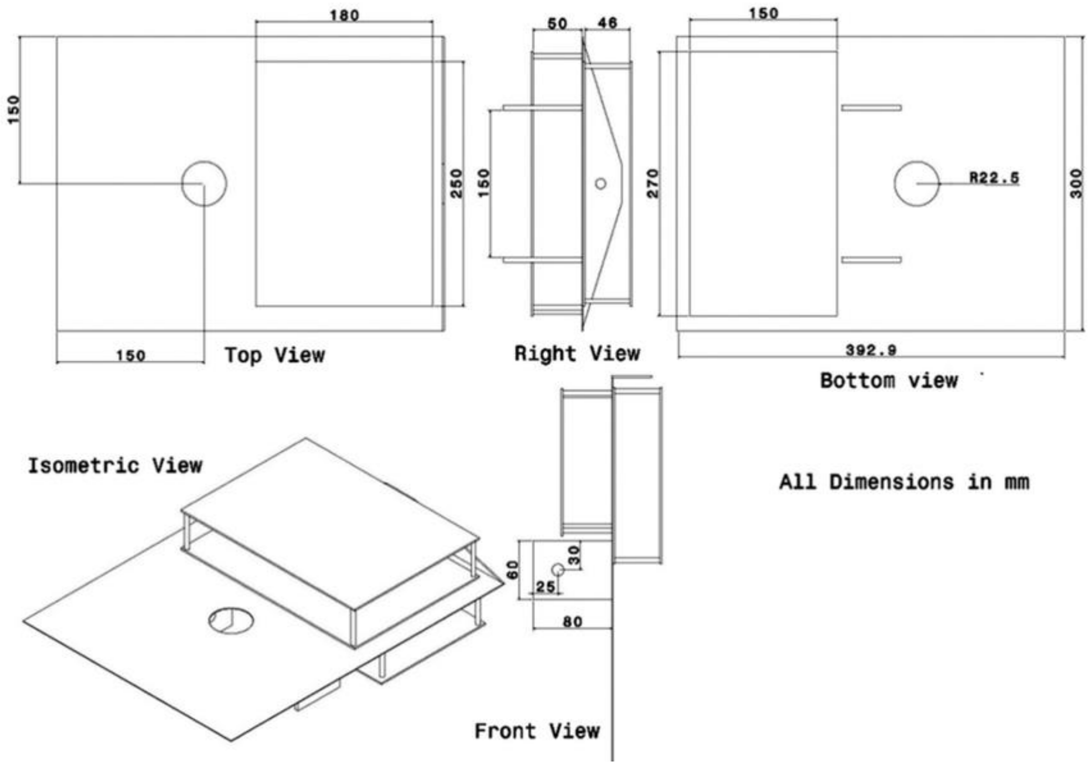


Fig.4.10 The Platform of the Mobile Robot

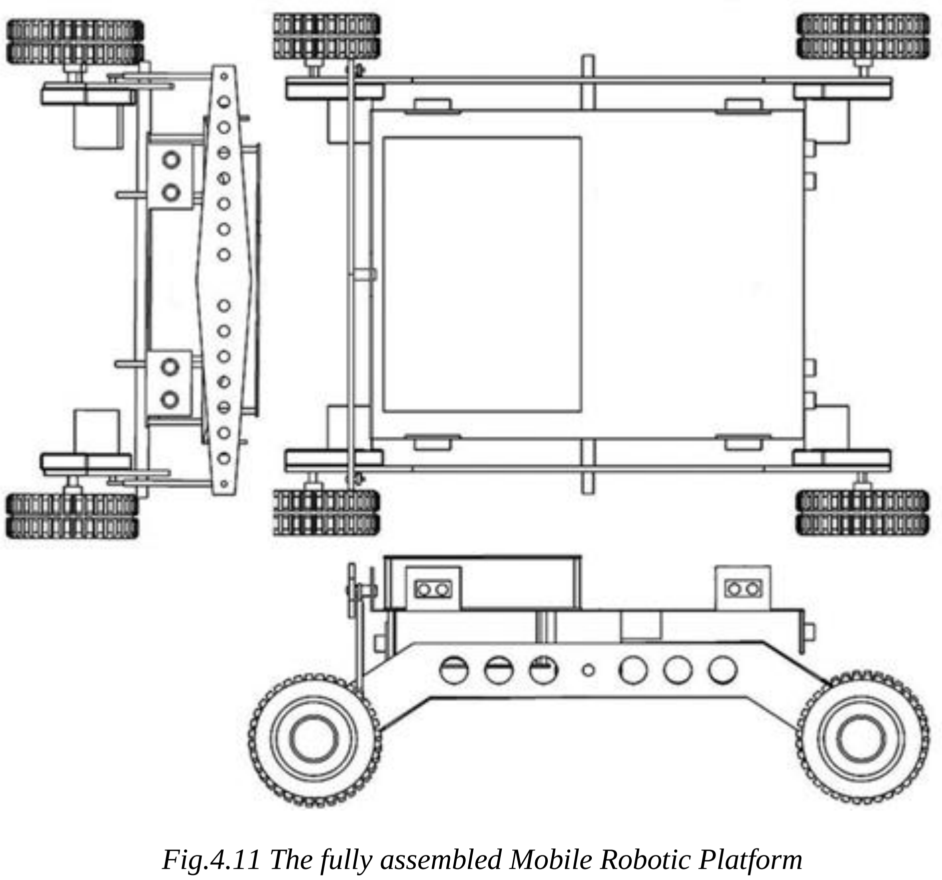


Fig.4.11 The fully assembled Mobile Robotic Platform

4.3 The Final Concept Design of the Mobile Robotic Manipulator

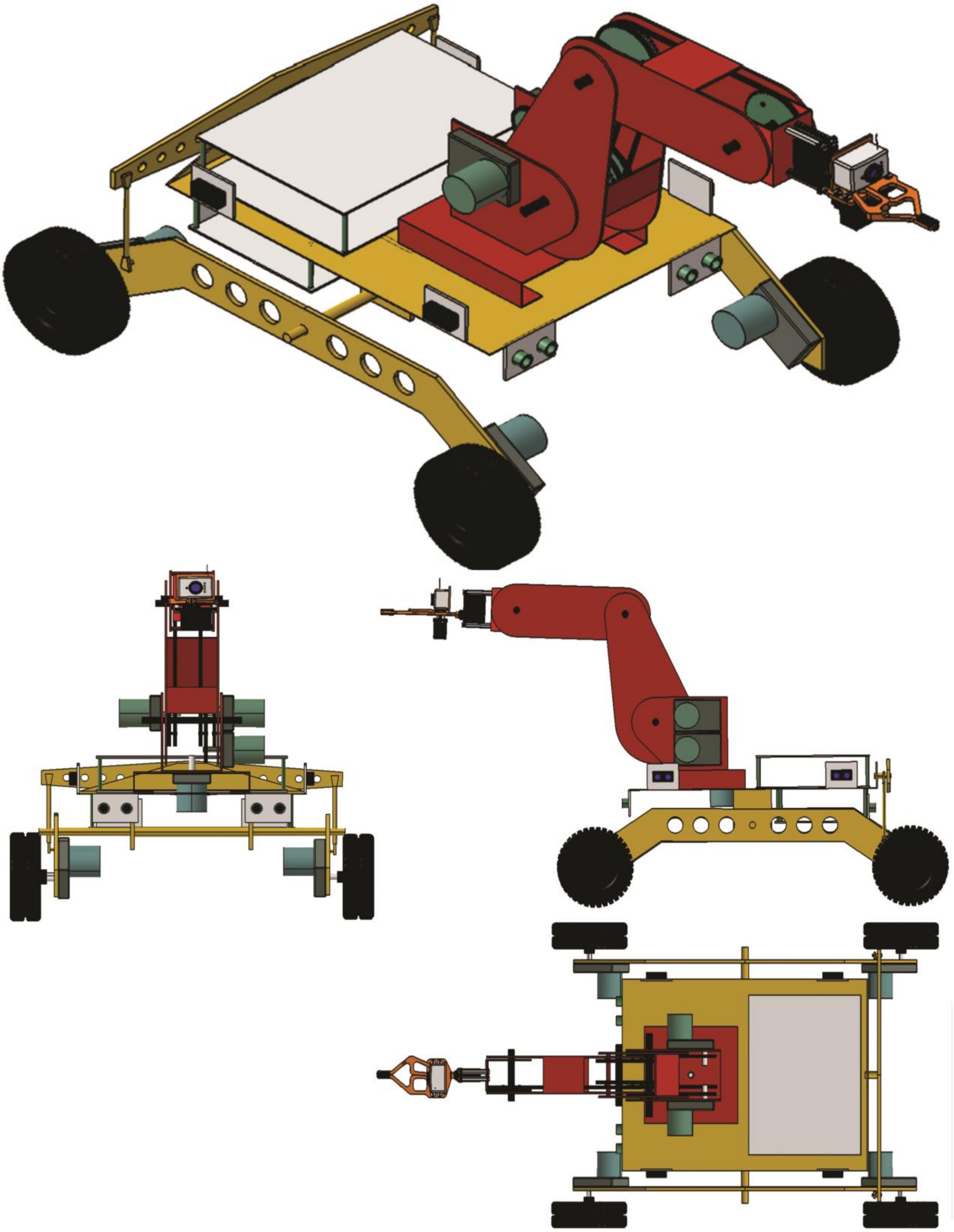


Fig.4.12 The final concept design of the Mobile Robotic Manipulator

4.4 Conclusion

This mobile manipulator is a unique robot comprising of a novel mobile platform with a robust manipulator built to meet few specific parameters and this chapter clearly presents the concept design for the mobile robotic manipulator using which the drawings for production are generated. Various components of the robot like: manipulator mechanism, suspension mechanism for the mobile platform and the gripper mechanisms have been presented.

FABRICATION PROCESS

Chapter 5

FABRICATION PROCESS

Design process is the integral part of Industrial Design and this project is an example for the effective utilization of design process. Starting from problem-statement/requirement to building a fully functional product, every single step of the design process has played a vital role in the success of this project.

Designing and building a robot from the scratch is a time consuming and lengthy process. There are numerous aspects which require detailed study and research before committing to it. Extreme care was taken to understand the problems involved in the project and find solutions for it. Each and every minute detail has been addressed very skilfully and tactfully.

Various machining processes available in the institute workshops were utilised to build this robot which took one and half years. The main processes involved in building this robot have been described in this chapter and they are: machining the manipulator body, machining the drive mechanism for the manipulator, machining the mobile platform, procuring the drives, sensors, control units, wheels, battery, etc., assembly of the machined parts and the procured products, setting up the controls, programming of the controls and testing the robot.

Various materials used to create different parts of the robot, various sensors incorporated and the controller used in the robot and a bill of materials are elucidated in this chapter.

5.1 Fabricating the Articulated Robotic Manipulator

The fabrication of the manipulator mainly involved three processes, namely: building the manipulator body, building its drive mechanism and fixing all the parts and components together. The motors and the other components used in the manipulator were decided before starting the work and using their dimensions we arrived at a design for the manipulator. The materials for creating various parts were selected considering the factors such as weight, forces, torque etc. that act on the parts.

5.1.1 Machining the Manipulator Body

Different parts of the manipulator experience forces and weights of different magnitudes and directions. Depending on this a suitable material has to be selected for each part. Using the selected material different parts of the manipulator like: base, body, upper-arm, forearm and end-effector housing were machined.

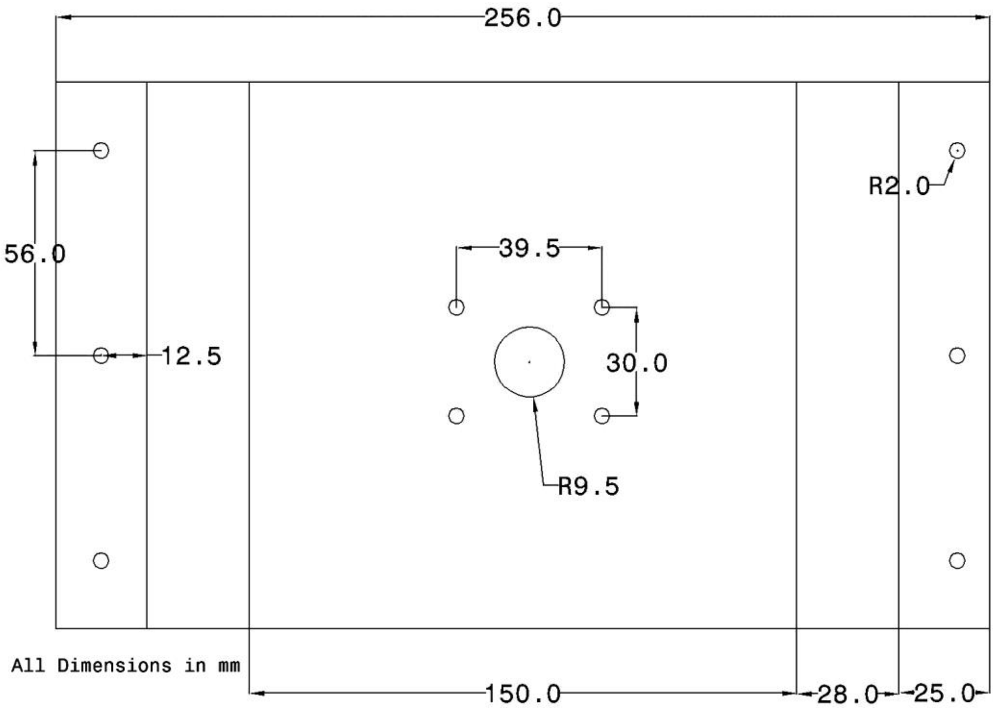


Fig.5.1 Base of the Manipulator

Part Name : Base of the Manipulator (*Fig.5.1)*

Material : 16 Gauge Mild Steel Plate

Machining Process :

- Jig-saw to cut the sheet in to required shape.
- Drill holes of various sizes using respective size drill bits.
- Bend the sheet using the bending machine at required spots to create the-necessary profile.

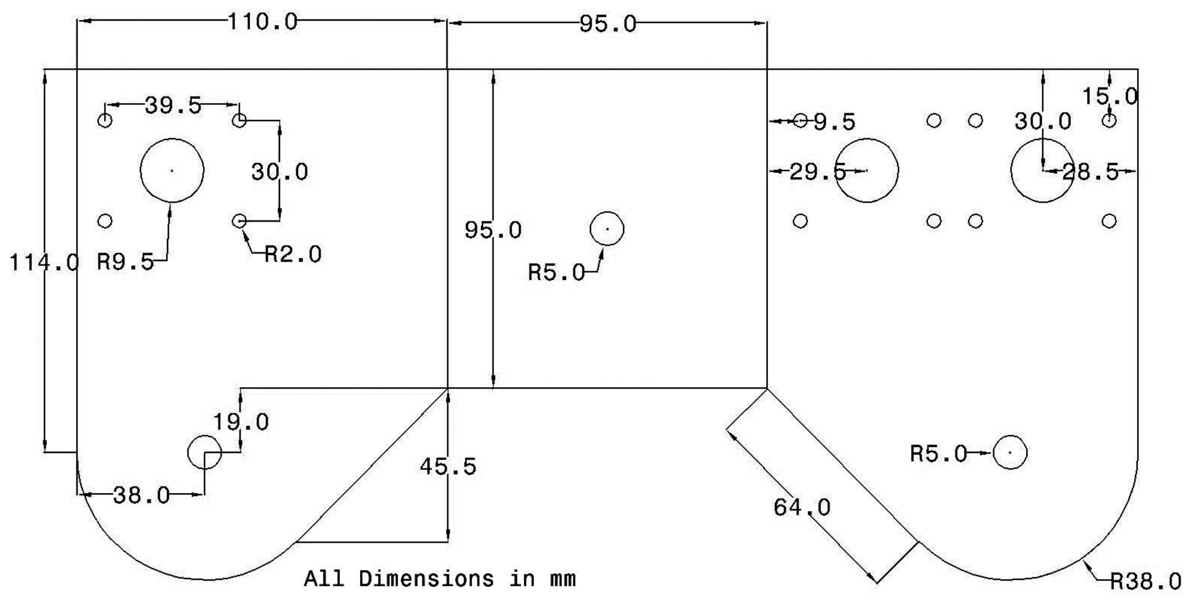


Fig.5.2 Body of the Manipulator

Part Name : Body of the Manipulator (*Fig.5.2*)

Material : 16 Gauge Mild Steel Plate

Machining Process :

- Jig-saw to cut the sheet in to required shape.
- Drill holes of various sizes using respective size drill bits.
- Bend the sheet using the bending machine at required spots to create the necessary profile.

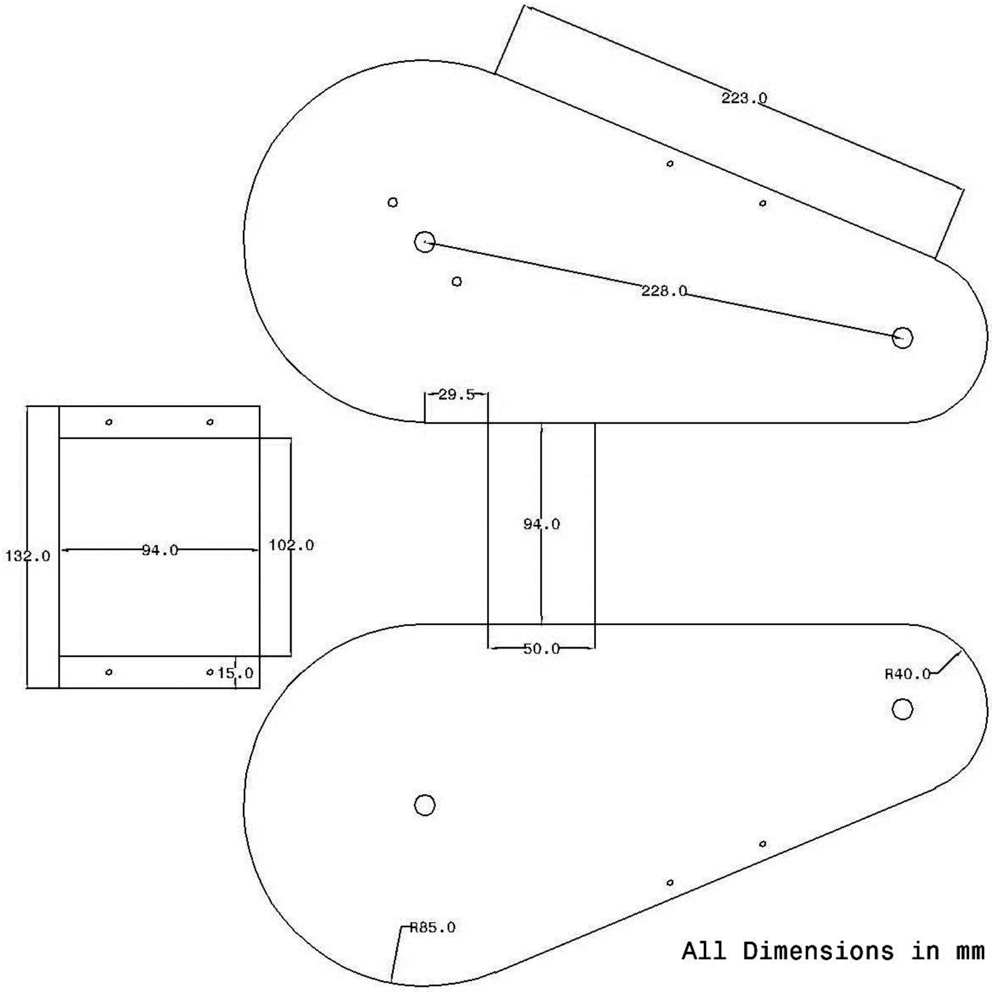


Fig.5.3 Arm Link 1 of the Manipulator

Part Name : Arm Link 1 (Upper-arm) of the Manipulator (*Fig.5.3*)

Material : 20 Gauge Galvanised Steel Plate

Machining Process :

- Jig-saw to cut the sheet in to required shape.
- Drill holes of various sizes using respective size drill bits.
- Bend the sheet using the bending machine at required spots to create the necessary profile.

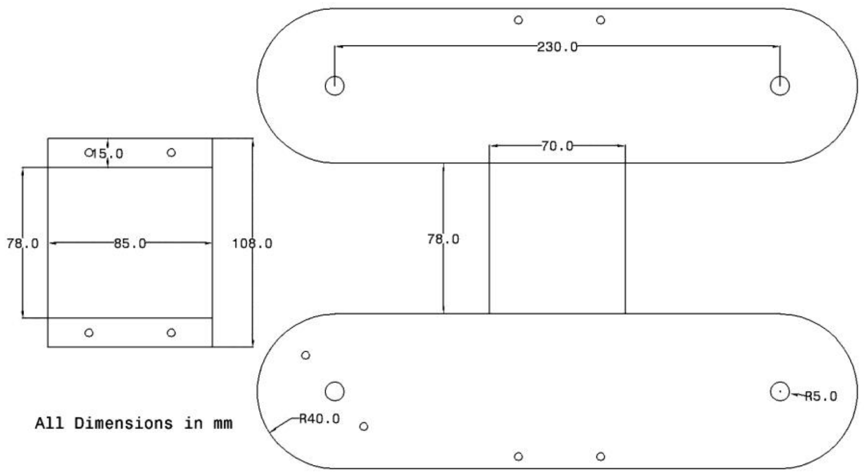


Fig.5.4 Arm Link 2 of the Manipulator

Part Name	:	Arm Link 2 (Forearm) of the Manipulator (*Fig.5.4*)
Material	:	20 Gauge Galvanised Steel Plate
Machining Process	:	• Jig-saw to cut the sheet into required shape. • Drill holes of various sizes using respective size drill bits. • Bend the sheet using the bending machine at required spots to create the necessary profile.

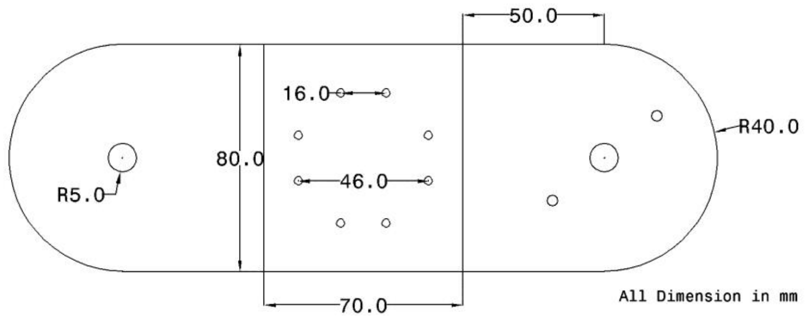


Fig.5.5 End-effector Housing of the Manipulator

Part Name	:	End-effector Housing of the Manipulator (*Fig.5.5*)
Material	:	20 Gauge Galvanised Steel Plate
Machining Process	:	• Jig-saw to cut the sheet in to required shape. • Drill holes of various sizes using respective size drill bits. • Bend the sheet using the bending machine at required spots to create the necessary profile.

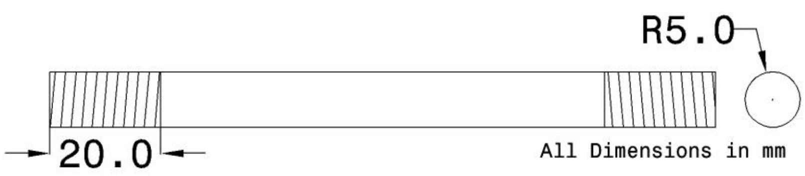


Fig.5.6 Axel of the Manipulator

Part Name : Axel of the Manipulator (*Fig.5.6*)

Material : 10mm diameter Stainless Steel Rods of lengths: 120mm, 100mm & 90mm

Machining Process :

- Cut the required length using a metal cutter/grinder machine.
- Using a threading die, the ends of the rods are threaded.
- Suitable nuts are procured for the threads

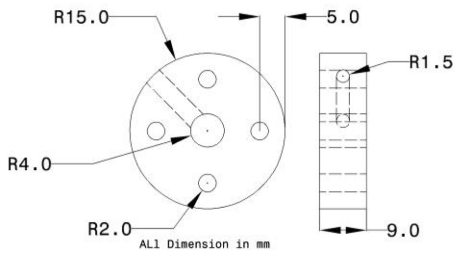


Fig.5.7 Mounting Hub for the Motor

Part Name : Mounting Hub for the Motor (*Fig.5.7*)

Material : 30mm diameter Mild Steel Rod of 10mm thickness

Machining Process :

- The rod is fixed on to the lathe and turned
- A hole is drilled through the centre of the rod using an 8mm drill bit
- Required length is cut out in the lathe itself.
- The 4mm holes and the 3.5mm side holes are drilled using a radial drilling machine
- These holes are threaded using a 4mm tap drill/threading bit.

5.1.2 Machining the Drive Mechanism of the Manipulator

The drive mechanism is the vital part of the manipulator. It is this part that actually runs the manipulator. A simple sprocket and chain mechanism is used in this manipulator. The working of drive mechanism has been explained earlier. As mentioned in the design specification, readily available chains and sprockets were chosen from the market.

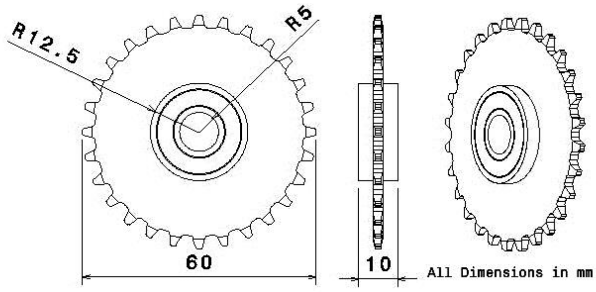


Fig.5.8 The Sprocket with Ball-Bearing for the Drive Mechanism

Part Name	:	Sprocket with Ball-Bearing for the Drive Mechanism (*Fig.5.8*)
Material	:	2.5mm thick Cast Iron Sprocket with 10mm diameter hole Ball-Bearing
Machining Process	:	• The Sprocket is fixed onto a lathe and the centre hole is increased to 24.5mm. • A 25mm outer diameter ball bearing is fixed tightly into the hole • It is spot welded and fixed firmly.

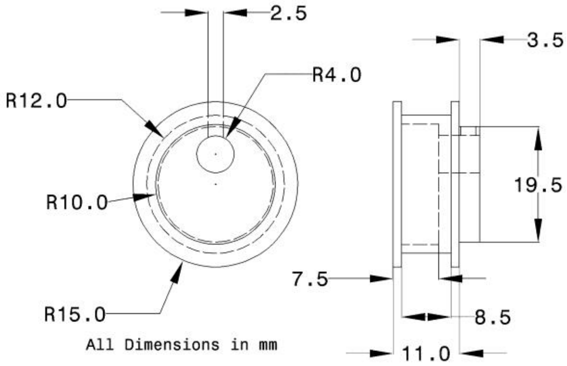


Fig.5.9 Chain Tightener for the Drive Mechanism

Part Name	:	Chain Tightener for the Drive Mechanism (*Fig.5.9*)
Material	:	30mm diameter Mild Steel Rod of 15mm thickness
Machining Process	:	• The rod is fixed on to the lathe and turned • A groove of 3mm is created for the chain to roll. • Required length is cut out in the lathe itself. • Using a radial drilling machine an 8mm hole is drilled, displaced from the centre; also a 3.5mm side hole is drilled. • The 3.5mm side hole is threaded using a 4mm tap drill/threading bit. • The piece is fixed to the lathe again and extra material is removed to reduce wait.

5.1.3 Assembling the Manipulator

The exterior parts of the body of the manipulator is well painted to give an asthetic appeal and also to protect it from rusting. The internal parts like ball-bearing, chains, and sprockets are well lubricated for lesser wear, smoother functioning and rust proofing. All the internal wiring, sensors and motors are fixed. And finally all the parts are put together to get the finished, fully functional articulated robotic manipulator (Fig.*5.10*)

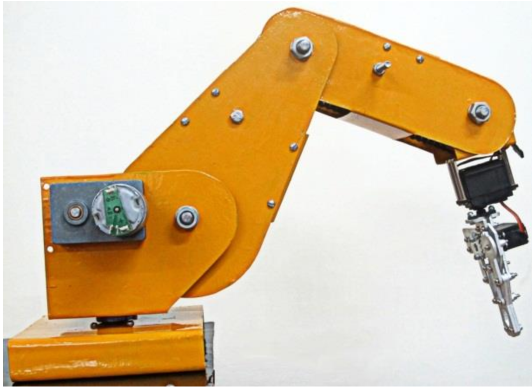


Fig.5.10 The Final Assembled Manipulator

5.2 Fabricating the Mobile Robotic Platform

The fabrication of the mobile robot primarily consists of building the suspension system for the mobile platform and fixing in the drives for mobility. The suspension system as explained earlier is a unique design which facilitates the robot to travel in uneven surfaces. The design and fabrication of the parts for this suspension system is the main task in building the mobile robotic platform.

5.2.1 Machining the Parts of the Suspension System of the Mobile Robot

As in the case of the manipulator the materials for the mobile robot have been chosen to withstand all the forces and weights acting on it.

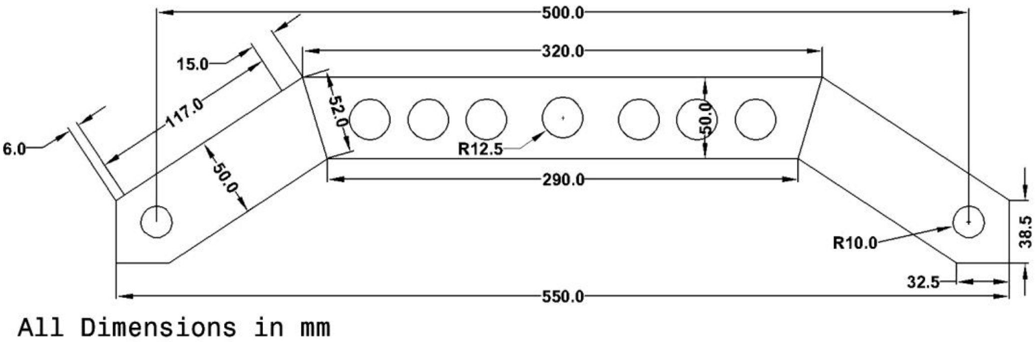


Fig.5.11 Rocker Frame of the Mobile Robot Suspension

Part Name	:	Rocker Frame of the Mobile Robot Suspension (*Fig.5.11*)
Material	:	5mm thick 50mm wide Mild Steel Flats
Machining Process	:	• Using a metal cutter/grinder machine the required shape is cut. • The pieces are welded together and grinded using surface grinding machine • Required holes are drilled on the frame. • Additional holes are added to reduce material from the frame.

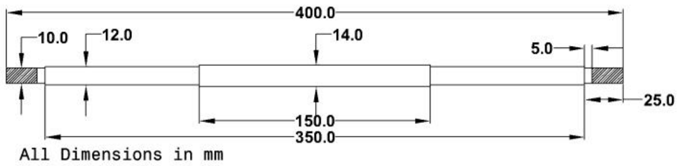


Fig.5.12 Central Axel of the Mobile Platform

Part Name : Central Axel of the Mobile Platform (*Fig.5.12*)

Material : 15mm diameter Mild Steel Rod of 400mm length

Machining Process :

- Cut the required length using a metal cutter/grinder machine.
- It is placed in a lathe and turned to required profile.
- Using a threading die the ends of the rod are threaded.
- Suitable nuts are procured for the threads.

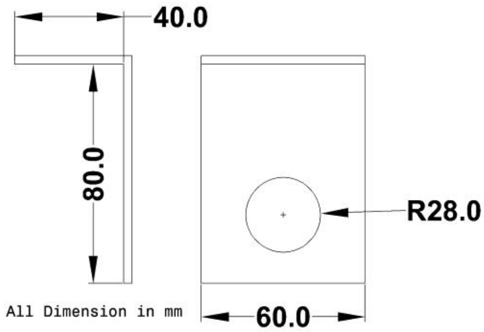


Fig.5.13 Support Frame for the Mobile Robot's Platform

Part Name : Support Frame for the Mobile Robot's Platform (*Fig.5.13*)

Material : 5mm thick 50mm wide Mild Steel Flats

Machining Process :

- Using a metal cutter/grinder machine the required shape is cut.
- The pieces are welded together and grinded using surface grinding machine
- Required holes are drilled on the frame.

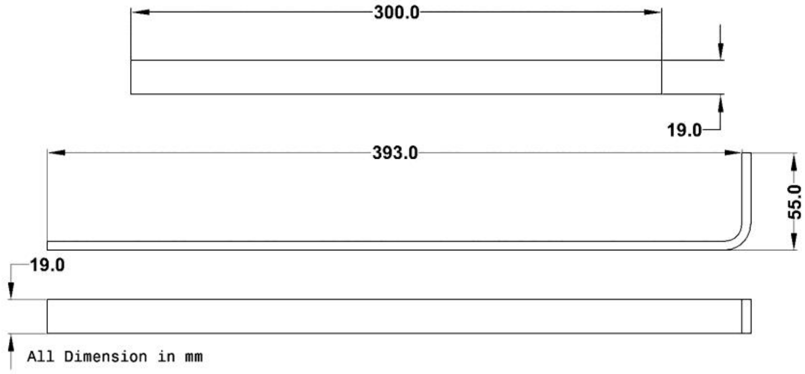


Fig.5.14 Support Frame Attachments

Part Name : Support Frame Attachments (*Fig.5.14*)

Material : 5mm thick 19mm wide Mild Steel Flats

Machining Process :

- Using a metal cutter/grinder machine the required length is cut.
- Required holes are drilled on the frame.
- The piece is grinded using a surface grinding machine and bend as required.

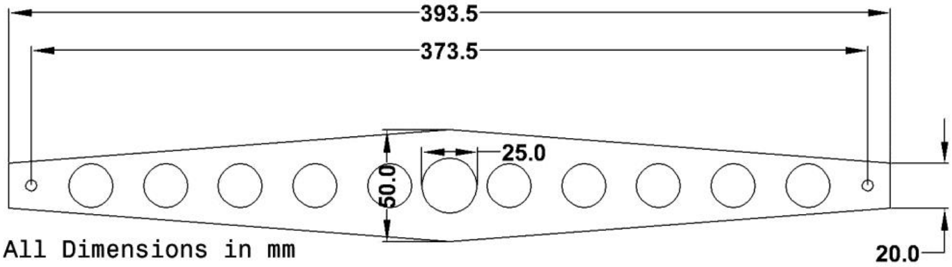


Fig.5.15 Cross Frame of the Mobile Robot Suspension

Part Name : Cross Frame of the Mobile Robot Suspension (*Fig.5.15*)

Material : 5mm thick 50mm wide Mild Steel Flats

Machining Process :

- Using a metal cutter/grinder machine the required shape is cut.
- Required holes are drilled on the frame.
- Additional holes are added to reduce material from the frame and grinded using surface grinding machine

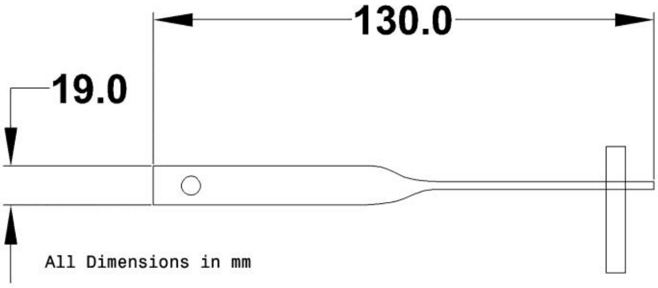


Fig.5.16 Connecting Rod connecting the Cross Frame and Rocking Frame

Part Name : Connecting Rod connecting the Cross Frame and Rocking Frame (*Fig.5.16)*

Material : 3mm thick 19mm wide Mild Steel Flats

Machining Process :

- Using a metal cutter/grinder machine the required length is cut.
- Required holes are drilled on to the frame.
- This piece is then twisted about the middle using hammer and anvil.

5.2.2 Assembling the Mobile Platform

All the parts are well painted to give it a good finish and appeal. The ball-bearings rotating on the central axis are well lubricated. All the parts are then assembled together and the motors and the encoders are fixed onto the rocking frames. Also, the wiring for the motors and the encoders are done. Finally a 110mm diameter 44mm thick wheel is coupled onto the motor shafts directly (Fig.*5.17*).

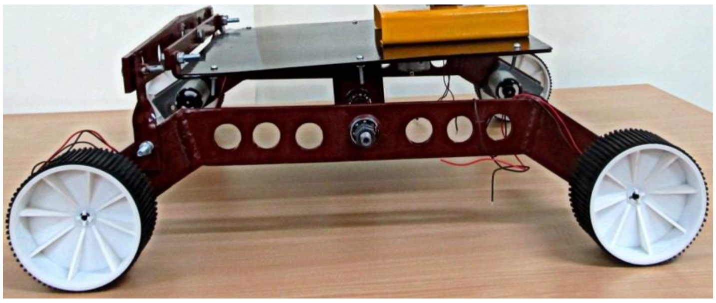


Fig.5.17 The Final Assembled Mobile Robotic Platform

5.3 List of Sensors Used

Numerous sensors have been used in this project to make it successful. These sensors play a vital role in the functioning of the robot. They are like the sense organs of a human being giving feedback of the surrounding. The signals received from the sensors are sent into the controller to make decisions. Thus by adding sensors the robot is made more versatile as it can make decisions on its own. List of the sensors used is given below in *Table 5.1* with a brief specification description.

Table 5.1 List of Sensors

Sensors	**Specifications**
A. Infra-Red Distance measuring sensor.	Range 100 to 800mm; Works on 5V; Communication: Analogue output voltage corresponds to distance (typically 0.4 to 2.3 V range)
B. Ultra Sound Distance measuring sensor.	Range 20 to 3000mm; Works on 5V; Communication: Positive TTL pulse; Frequency 40 KHz; Continual Response Time : 5ms
C. Tactical Sensors/Switches Obstacle & collision sensing.	It is basically a switch with a long handle which closes the switch every time when it collides with an obstacle.
D. Pressure Sensor Force Sensing Resistors.	Load capacity: 11.34Kg; Sensing area: 9.53mm diameter circle; Material: Substrate Polyester (ex: Mylar); Response Time: Lesser than 5 μsec.
E. Camera Wireless video capture.	360x280 pixels camera; Working voltage from 5V to 12V; Inbuilt Microphone; Transmits audio along with video; Range up to 25 feet in open space.

5.4 Bill of Materials

A brief bill of materials used in building this robot has been stated below in *Table 5.1*.

Table 5.2 Bill of Materials

	Material Used / Process involved in manufacturing it	Size/Dimensions	Number of pieces
1	16 Gauge Mild Steel Plate	400x900mm	1
2	20 Gauge Galvanised Steel Plate	1200x1200mm	1
3	10mm diameter Stainless Steel Rod	400mm	1
4	30mm diameter Mild Steel Rod	600mm	1
5	5mm thick 50mm Mild Steel Flats	2000mm	1
6	15mm diameter Mild Steel Rod	600mm	1
7	5mm thick 19mm Mild Steel Flats	2000mm	1
8	Chain type 25	-	6
9	Sprocket with 14 teeth	-	3
10	Sprocket with 28 teeth	-	9
11	Ball-Bearing with hole diameter 10mm	-	11
12	Ball-Bearing with hole diameter 12mm	-	2
13	10 RPM Side Shaft Super Heavy Duty DC Gear Motor	-	8
14	DC Motor Driver	-	8
15	Position Encoder Kit	-	8
16	4Kg-cm torque, High Performance Servo Motor	-	2
17	Arduino Mega 2560	-	1
18	Gripper Assembly	-	1
19	Infra-Red Sensor	-	4
20	Ultra Sound Sensor	-	4
21	Tactical Sensors/Switches	-	10
22	Force Sensing Resistor	-	1
23	Wireless Transmission Camera	-	1
24	Wheel for the Mobile Base	-	4
25	Battery	-	1
26	Miscellaneous	-	-

Note: Miscellaneous include the mechanical parts, nuts and bolts, wires and cables, electronic components etc.

Fig.5.18 The Mantis

5.5 Conclusion

This robot has few distinctive parts that define its basic shape and structure which are not readily available off the shelf and had to be designed and fabricated exclusively. Moreover, that way the total cost of the robot could be contained to a very minimum and also a very concrete know-how of the processes involved in developing a totally new component could be studied and documented.

ARTIFICIAL INTELLIGENCE

FOR PATH PLANNING

Chapter 6

ARTIFICIAL INTELLIGENCE FOR PATH PLANNING

"…the brain that makes up perceptions and emotions operate in a binary fashion…"
– Bill Gates

This quote sums up man's struggle to understand *the thinking process* from a technologist's point of view. How can brain make decisions, predict outcomes, perceive, understand and control things much bigger than he is, has always intrigued humans. This fascination towards intelligence gave birth to Artificial Intelligence (AI), which led him to make entities that can almost think and do things like he does. Design and development of control techniques for autonomous robot that can operate in unknown, unpredictable, organised and unorganised environments is an interesting area of research that has seen many innovative outcomes over the years.

This chapter intends to address research developments in the area of AI techniques for the control of mobile robots. Two popular techniques used in Mantis are: Fuzzy Logic Controller and Genetic Algorithm Technique. These techniques are executed in various environments and it has been briefly explained in this chapter.

6.1 Fuzzy Logic Controller for Mobile Robots

Human intelligence is highly adaptive. It can perform a wide variety of physical and mental tasks with no precise or numerical information. This human ability to function and reason with perception based information forms the basis of fuzzy logic controller. This unique problem solving control system can be used in many fields ranging from small electronic components to complex robot and network systems. In a very scientific approach this rule-based fuzzy logic mimics the decision making and reasoning capability of human beings with imprecise and inexact information. The main advantage in this approach is the ability to derive heuristic rules from human experience and remove the need for analytical models [86, 87].

The proposed fuzzy controller takes inputs picked up by the sensors mounted on Mantis. The inputs comprise of the target angle and the distance between the robot and the specified target and also the obstacle location from front, left and right side of Mantis. The target angles located at the left side of the robot is taken as negative and on the right side as positive. The output of the controller is the wheel speeds. Schematic representation of the same is shown in *Fig.6.1*. Here front obstacle distance (f.o.d.), left obstacle distance (l.o.d.), right obstacle distance (r.o.d.) all in mm and target angle (t.a.) in degrees are the inputs and velocity of the right side wheels and left side wheels in m/s are the outputs.

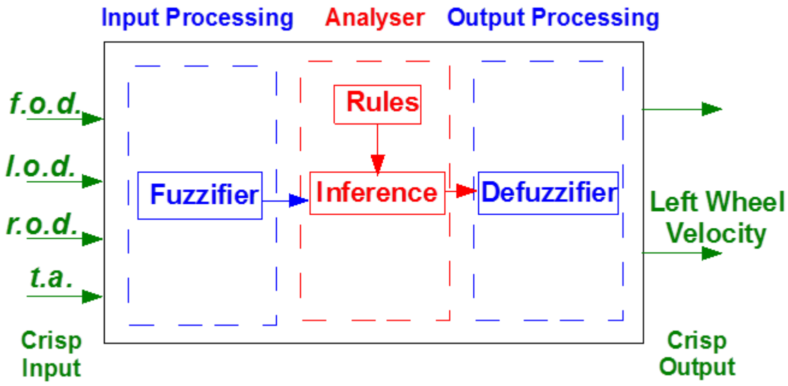


Fig.6.1 Schematic Representation of the Fuzzy Logic Controller

The four principle elements that make a basic fuzzy controller configuration are: fuzzifier, fuzzy rule base, inference engine and defuzzifier.

Fuzzifier

Fuzzifier is a mapping from the crisp input data to corresponding fuzzy sets, which forms the input for the inference engine and simplifies the computation in the inference engine. These fuzzy sets basically consist of membership functions whose values range from 0 to 1.Linguistic variables near, medium and far are used to fuzzify the input data f.o.d., l.o.d. and r.o.d. The target angle (t.a) is fuzzified using linguistic variable positive (P), zero (Z) and negative (N), while the output data, i.e. the wheel velocities is fuzzified using slow, med.(Medium) and fast (*Table 6.1*).

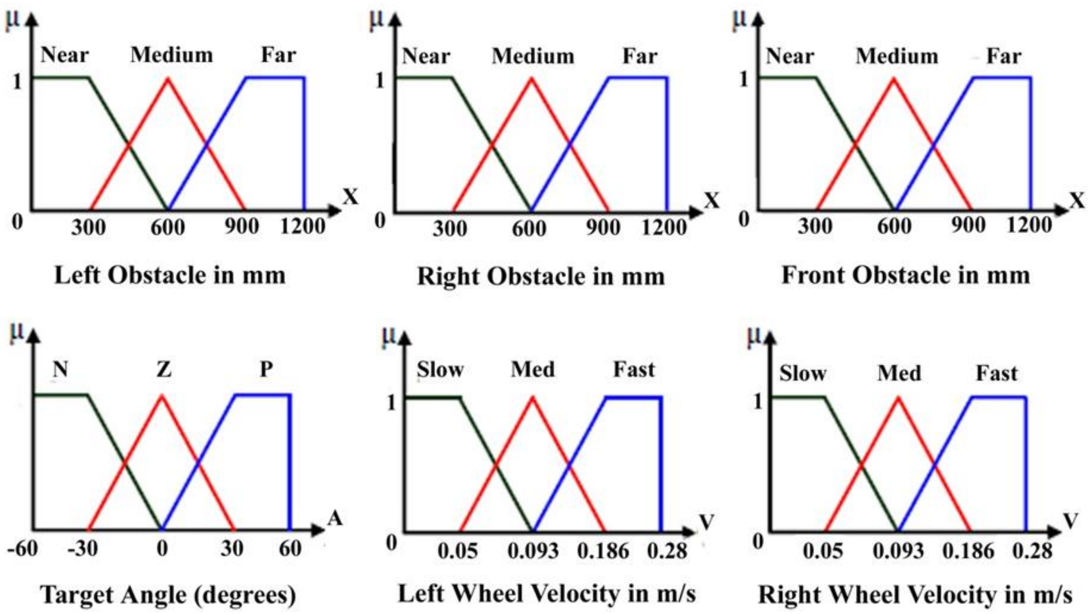


Fig.6.2 Fuzzy membership functions used to design fuzzy logic controller

Table 6.1 Parameters for Variables

Front Obstacle Distance (f.o.d.) Left Obstacle Distance (l.o.d.) Right Obstacle Distance (r.o.d)	Near (mm)	Medium (mm)	Far (mm)
	0 to 600	300 to 900	600 to 1200
Target Angle (t.a.)	Negative	Zero	Positive
	-60° to 0°	-30° to +30°	0° to 60°
Left Wheel Velocity (l.v.) Right Wheel Velocity (r.v)	Slow (m/s)	Med. (m/s)	Fast (m/s)
	0 to 0.093	0.05 to 0.186	0.093 to 0.28

Analyzer

Rule Base:

The fuzzy rule base is basically a knowledge base of linguistic rules in IF-THEN form, i.e. "*if a set of conditions are satisfied, then a set of outcomes result*". In this fuzzy system with four inputs and two outputs the general fuzzy rule base consists of the following.

IF "the matching degree of l.o.d. $x_1$is $\mu_A(x_1)$, the matching degree of r.o.d. x_2 is $\mu_A(x_2)$, the matching degree of f.o.d. x_3 is $\mu_A(x_3)$ and matching degree of t.a. x_4 is $\mu_A(x_4)$" *THEN* "the matching degree of l.v. v_l is $\mu_A(y_i)_l$ and the matching degree of r.v. v_r is $\mu_A(y_i)_r$".

Inference Engine:

The inference method is Min-Max where implication is minimum and aggregation is maximum.

Using the following formula the matching degree of the final output is computed.

$$Matching\ Degree\ \mu_A(y_i)_{l,r} = min\{\mu_A(x_1), \mu_A(x_2), \mu_A(x_3) and\ \mu_A(x_4)\} \tag{6.1}$$

where, i=(1,2,…n) is the rule used, x_1, x_2, x_3 and x_4 are sensor inputs of l.o.d., r.o.d., f.o.d. and t.a. respectively, $\mu_A(x_1)$, $\mu_A(x_2)$, $\mu_A(x_3)$ and $\mu_A(x_4)$ are the corresponding matching degrees of the sensor inputs and $\mu_A(y_i)_l$ and $\mu_A(y_i)_r$ are the matching degrees of left and right wheel velocity respectively inferred from the inputs.

The conclusion is identical to the rule's consequence if the matching degree is 1 and no conclusion can be inferred if it is 0.

Aggregation:

Following formula gives the firing output area of the left and right wheel velocity.

$\mu_A(y_i)_{l,r} = max\{\mu_A(x_1), \mu_A(x_2), \mu_A(x_3) and\ \mu_A(x_4)\}$(6.2)

Defuzzification

The final crisp value of the left and right wheel velocity from the fuzzy logic controller is calculated by

$$Wheel\ Velocity, V_{l,r} = \frac{\sum_{i=0}^{n} \mu_A(y_i) \times (z_i)}{\sum_{i=0}^{n} \mu_A(y_i)} \quad (6.3)$$

where, z_i is the centroid distance of the firing area $\mu_A(y_i)_{l,r}$ of the left and right wheel velocity for the i^{th} rule, $V_{l,r}$ is the velocity of the left and right wheel and n is the total number of parameters. The method of defuzzification mentioned above is known as Centroid of Area (COA) method.

Mantis needs the following behavioural characteristics like target seeking, wall following and obstacle avoidance to reach a specified destination. In biology behaviour basically means how an organism or system reacts to some external stimulation and in case of mobile robots this behaviour is path following or obstacle avoidance. Mantis has 4 ultrasound and 4 infra-red sensors for distance measuring and to obtain target angle and fuzzy control rules are activated according to the information received from these sensors. The velocities of the wheels are obtained from the defuzzified results of the activated rules.

6.1.1 Obstacle Avoidance Behaviour

The sensors on the robot input information of the surrounding continuously. If these sensors send in an input of an obstacle being very close to the robot, then it has to make a decision to slow down and change its steering angle to avoid the obstacle. This enables the robot to avoid both static and dynamic load.

When manoeuvring around a corner or narrow turn the robot has to slow down to avoid collision. Thus deceleration becomes the reactive behaviour in this case. The rules that govern the obstacle avoidance behaviour of the robot are given in *Table 6.2*.

The second and third rules for the above case can be re-written as follows:

If (l.o.d. is near and r.o.d. is near and f.o.d. is medium and t.a. is any) Then (l.v. is slow and r.v. is slow).

If (l.o.d.is near and r.o.d.is near and f.o.d.is far and t.a. is any) Then (l.v. is med. and r.v. is med.).

Simulation for static obstacle avoidance has been shown in *Fig.6.3*.

Table 6.2. List of rules for obstacle avoidance

Rule No.	*Action*	*l.o.d.*	*r.o.d.*	*f.o.d.*	*t.a.*	*l.v.*	*r.v*
1	OA	Near	Near	Near	Any	Slow	Fast
2	OA	Near	Near	Medium	Any	Slow	Slow
3	OA	Near	Near	Far	Any	Slow	Slow
4	OA	Near	Medium	Near	Any	Med.	Slow
5	OA	Near	Medium	Medium	Any	Med.	Slow
6	OA	Near	Medium	Far	Any	Med.	Med.
7	OA	Near	Far	Near	Any	Fast	Slow
8	OA	Near	Far	Medium	Any	Med.	Slow
9	OA	Near	Far	Far	Any	Fast	Med.
10	OA	Medium	Medium	Near	Any	Fast	Slow
11	OA	Medium	Medium	Medium	Any	Slow	Slow
12	OA	Medium	Medium	Far	Any	Fast	Fast
13	OA	Medium	Near	Near	Any	Slow	Fast
14	OA	Medium	Near	Medium	Any	Slow	Med.
15	OA	Medium	Near	Far	Any	Slow	Slow
16	OA	Medium	Far	Near	Any	Med.	Slow
17	OA	Medium	Far	Medium	Any	Med.	Fast
18	OA	Medium	Far	Far	Any	Fast	Med.
19	OA	Far	Near	Near	Any	Slow	Fast
20	OA	Far	Near	Medium	Any	Med.	Fast
21	OA	Far	Near	Far	Any	Med.	Fast
22	OA	Far	Medium	Near	Any	Slow	Fast
23	OA	Far	Medium	Medium	Any	Slow	Med.
24	OA	Far	Medium	Far	Any	Med.	Fast
25	OA	Far	Far	Near	Any	Fast	Slow
26	OA	Far	Far	Medium	Any	Fast	Med.
27	OA	Far	Far	Far	Any	Fast	Fast

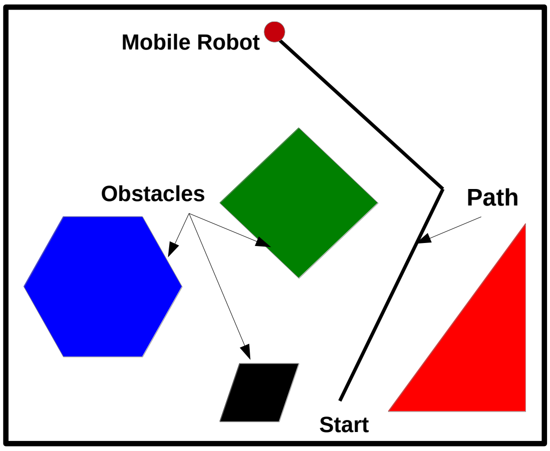


Fig.6.3 Static obstacle avoidance simulation

6.1.2Wall Following Behaviour

Consider a situation where the mobile robot moves through a large C shaped obstacle. When it initially detects an obstacle it takes a left turn as it is blocked on the right. It keeps continuing in that direction till it meets another obstacle and now it is forced to turn right as the target is at the right side and it keep continuing in that direction till it meets a wall and now it turns left depending on the previous decision and this process continues in an indefinite loop with no particular result.

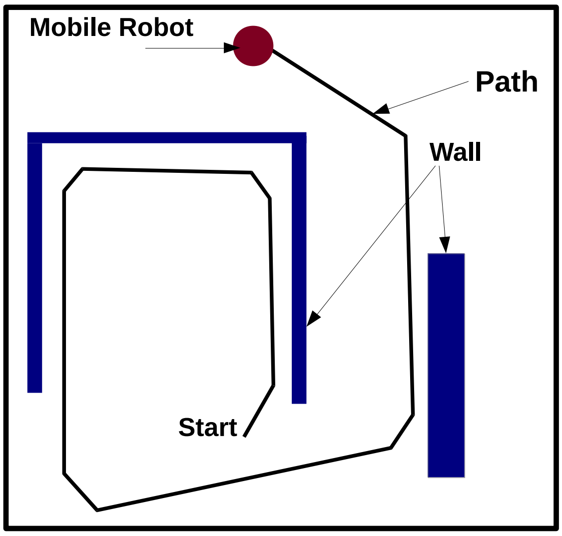


Fig.6.4 Wall following behaviour simulation

Hence when avoiding a dead end obstacle or C shaped obstacle or the robot is moving through a narrow path then the wall following behaviour is highly useful as shown in *Fig.6.4*. The resulting rule base is stated in *Table 6.3*.

These fuzzy rules help a mobile robot to follow a wall or an edge of an obstacle very close to its left or right side when the target is at the left or right. This behaviour is dependent on the angle between the robot and the target.

Table 6.3. List of rules for wall following behaviour

Rule No.	*Action*	*l.o.d.*	*r.o.d.*	*f.o.d.*	*t.a.*	*l.v.*	*r.v.*
28	WF	Far	Far	Near	Any	Med.	Slow
29	WF	Far	Medium	Near	Any	Slow	Med.
30	WF	Medium	Far	Near	Any	Fast	Med.
31	WF	Near	Far	Medium	Any	Fast	Med.
32	WF	Near	Far	Near	Any	Fast	Med.
33	WF	Near	Medium	Far	Any	Med	Slow

6.1.3Target Seeking Behaviour

When the input information provided by the sensors prove that there are no obstacles around, then the primary concern of the controller is target seeking and sending the robot in the desired direction. The following *Table 6.4* provides the rule base for target seeking behaviour of the robot. The *Fig.6.5* shows the target seeking capability in simulation.

Table 6.4. List of rules for target seeking

Rule No.	*Action*	*l.o.d.*	*r.o.d.*	*f.o.d.*	*t.a.*	*v.l.*	*v.r*
34	TS	Far	Far	Far	P	Fast	Med.
35	TS	Far	Far	Medium	N	Med.	Fast
36	TS	Far	Far	Far	Z	Fast	Fast
37	TS	Far	Far	Medium	P	Slow	Med.
38	TS	Far	Medium	Far	N	Med.	Fast
39	TS	Medium	Far	Far	Z	Fast	Fast

IF "the l.o.d. is Far, the r.o.d. is Far, the f.o.d. is Far and the t.a. is P" THEN "the v.l. is Fast and the v.r is Med.)

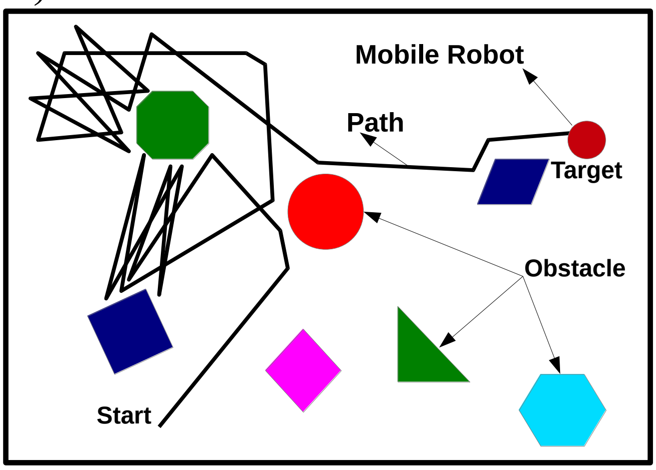


Fig.6.5 Target seeking behaviour simulation

6.2 Genetic Algorithm Technique for Mobile Robots

This section deals with how Genetic Algorithms can be used to analyse and optimize the path for Mantis's navigation. Genetic algorithm is based on the mechanics of biological evolution. It was designed primarily to develop system that has the robustness and adaptive capability of natural systems and to understand processes involved in natural systems. Genetic Algorithm is a stochastic algorithm which does not use gradient information and finds the best use when the objective function is discontinuous, highly non-linear, has unreliable or undefined derivatives and has high dimension. One disadvantage of this system is it is not fast enough to cover large space, though it is capable of quickly finding promising regions it takes relatively long time to reach an optimal solution.

Genetic Algorithms operate on a population of chromosomes which is likely to produce solutions for the given problem. A variation is introduced by applying two operators: crossover and mutation and finally a fitness criterion is used to bias the evolution towards desired features, which is nothing but the survival of the fittest. The techniques common in this unique class of evolutionary algorithm are: crossover or recombination of parent chromosomes, the inheritance of the characteristics from the parent chromosome, mutation to avoid similarity and natural selection process to improve the selection criteria.

Here population is a group of chromosomes available for testing and a chromosome is a string of genes that represents a solution. A gene is a single bit or short block of adjacent bits that encode an element of the candidate solution i.e. a single encoding part of the solution space.

In this new approach to path planning and obstacle avoidance each chromosome is represented as a group of basic elements and with the help of the feedbacks generated from the environment these elements define the robot's movement. The feedback is nothing but the input to the control system based on the sensor reading and the direction of the robot to its target. As stated before Mantis has 4 ultrasonic and 4 infra-red sensors for detecting obstacle and the target angle.

The basic input parameters to a genetic controller in case of a mobile robot is front obstacle distance (f.o.d.), left obstacle distance (l.o.d.) and right obstacle distance (r.o.d.) and the output is the heading angle (h.a.).These inputs and outputs are expressed in terms of encoded generation function distributions by crisp values. To interface with machine language for further processing these crisp values are transformed to binary values. They can be easily visualized in the following stages:

Stage 1: Formation of pool set for obstacle avoidance

For a predefined population size a population pool is created from the sensor input data. Each chromosome in the population represents a solution, i.e. the heading angle of the robot. The initial population with size 'n' can be presented as follows.

Initial Population = $(P_1, P_2, \dots \dots . P_n)$

Every population has a set of five chromosomes represented by Element No. 1 to 5 and these elements $p_{(i,i)}$ are integers representing the length.

			Element No.1	Element No.2	Element No.3	Element No.4	Element No.5	
$P_1,$	=	{	$p_{(1,1)}$	$p_{(1,2)}$	$p_{(1,3)}$	$p_{(1,4)}$	$p_{(1,5)}$	}
$P_2,$	=	{	$p_{(2,1)}$	$p_{(2,2)}$	$p_{(2,3)}$	$p_{(2,4)}$	$p_{(2,5)}$	}
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$P_n,$	=	{	$p_{(n,1)}$	$p_{(n,2)}$	$p_{(n,3)}$	$p_{(n.4)}$	$p_{(n,5)}$	}

where, Element No.1 ($p_{(1,1)} to\ p_{(n,1)}$) represent the front obstacle distance (f.o.d.).

Element No.2 ($p_{(1,2)} to\ p_{(n,2)}$) represent the left obstacle distance (l.o.d.).

Element No.3 ($p_{(1,3)} to\ p_{(n,3)}$) represent the right obstacle distance (r.o.d.).

Element No.4 ($p_{(1,4)} to\ p_{(n,4)}$) represent instantaneous heading angle (h.a.) with respect to the target position.

Element No.5 ($p_{(1,5)}\ to\ p_{(n,5)}$) represents the sign conventions (+ve, -ve and zero) for clockwise, anti-clockwise and straight based on the direction of the heading angle as shown in (*Fig.6.6*).

A region is treated obstacle free if there are no obstacles in a distance of 1000mm radius, so the robot heads towards the target in that particular direction till it finds an obstacle within its range (*Case 5 in Table 6.5*).

If the obstacle distance to the left is medium, to the right is near and the front is near then the robot takes a left turn (*Case 2 in Table 6.5*). Similarly, if the obstacle distance to the left is near, to the right is medium and the front is near then the robot takes a right turn (*Case 8 in Table 6.5*).

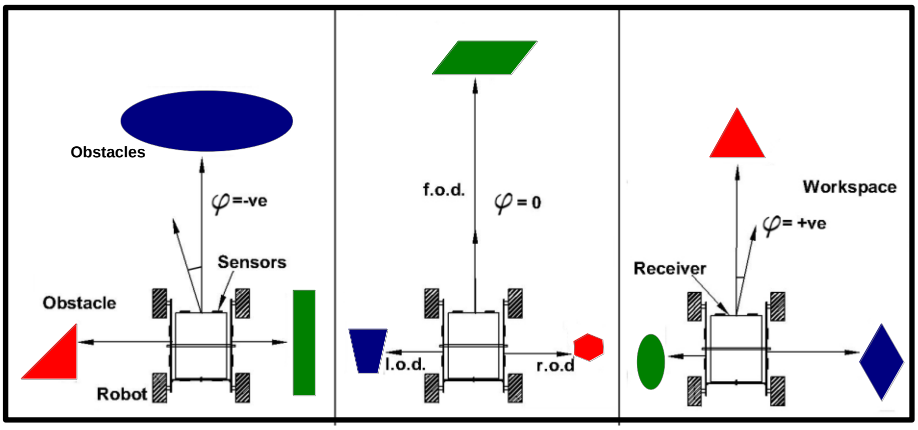


Fig.6.6 Sign convention of GA output in terms of heading angle (h.a.) with respect to obstacle position.

Table 6.5 Heading Angle with Respect to Different Obstacle Position

Case	*f.o.d. (mm)*	*l.o.d. (mm)*	*r.o.d. (mm)*	*h.a. (φ) (Degree)*	*Direction (+/-)ve*
1	490	390	290	18	-ve
2	590	670	510	12	-ve
3	780	590	290	10	-ve
4	530	550	310	15	-ve
5	1170	200	230	0	Straight
6	990	780	550	5	+ve
7	940	430	880	14	+ve
8	230	390	700	12	+ve
9	980	200	880	16	+ve
10	630	880	350	10	+ve

Stage 2: Analysis of fitness function for obstacle avoidance

Fitness function is responsible for the optimal obstacle avoidance of the robot as it quantifies the optimality of a solution or chromosome to be ranked against all the other solutions. It basically represents the closeness of the solution to the desired result. A fitness function is selected for obstacle avoidance of the robot with optimum heading angle with respect to the target location. The fitness value for a complete solution is computed as:

$$f_{Total} = w_1(f_1) + w_2(f_2) + w_3(f_3) + w_4(f_4) + w_5(f_5) \tag{6.4}$$

where, $$f_1 = \sqrt{\{(C_{f.o.d.} - p_{ci,1})^2 + (C_{l.o.d.} - p_{ci,2})^2 + (C_{r.o.d.} - p_{ci,3})^2\}} \tag{6.5}$$

$$f_2 = \left|C_{f.o.d.} - p_{ci,1}\right| \tag{6.6}$$

$$f_3 = \left|C_{l.o.d.} - p_{ci,2}\right| \tag{6.7}$$

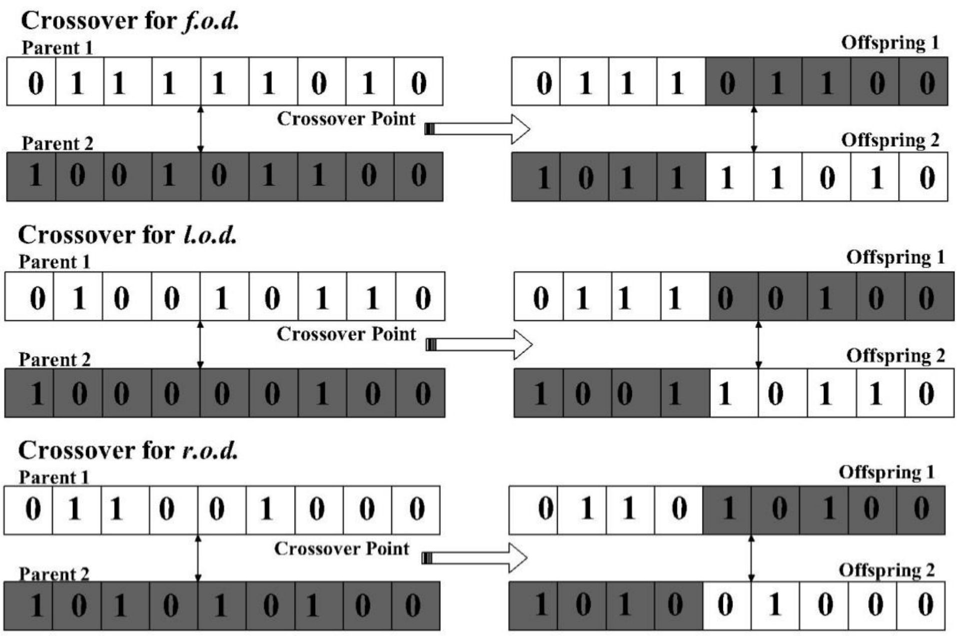
$$f_4 = \left|C_{r.o.d.} - p_{ci,3}\right| \tag{6.8}$$

$$f_5 = |TA - HD| \tag{6.9}$$

$(C_{f.o.d.} - p_{ci,1}), (C_{l.o.d.} - p_{ci,2})$ and $(C_{r.o.d.} - p_{ci,3})$ are the best distances (child) obtained from the given pool set of front, left and right obstacles distances from instantaneous obstacle position with respect to initial position.TA and HD are the target angle and heading direction respectively. The coefficients of the fitness function $w_1 - w_5$ are to be computed statistically using fuzzy inference technique.

Stage 3: Crossover of parameters and its analysis

A genetic operator that combines two parent chromosomes to produce two new offspring is called crossover. The resulting chromosome may be better than both the parent chromosomes, if it takes the best characteristics from each. In the present work the crossover operator has been modified within the crossover probability to produce two offspring chromosomes by applying a single-cross-point value encoding crossover. To create two offspring chromosomes, the gene information which are not used to build the offspring 1 are used to build the offspring 2, this can be seen in *Fig.6.7*. The basic functioning of a single-point crossover operator is: choose a random point, split the parent chromosomes at this crossover point and create the offspring by exchanging genes. The probability of crossover typically ranges between (0.6, 0.9).



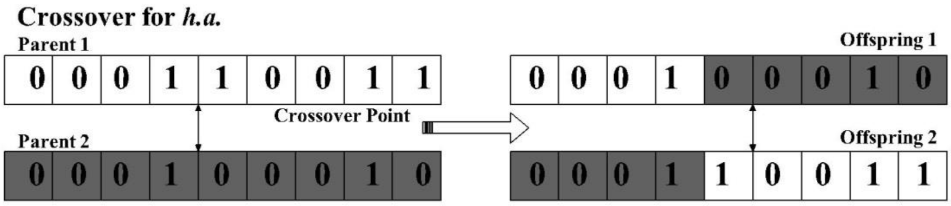


Fig.6.7 Single-Cross-Point, value-encoding crossover for f.o.d., l.o.d., r.o.d. and h.a.

Stage 4: Mutation

The genetic operator that maintains a genetic diversity from one generation of population of chromosome to the next is called a mutation and this is very similar to biological mutation. They basically change the order of the gene in a chromosome or change a gene's value. To determine how often the parts of a chromosome will be mutated, we use mutation probability and it ranges between [(1/population size), (1/chromosome length)]. As a result complete search space will be explored and thus prevents GA from getting stuck at local optimum.

Stage 5: Evaluation of fittest child according to fitness function

Using the fitness function described in stage 2 the evaluation of the fittest child is computed. The flowchart (*Fig. 6.8*) shows the outline of the proposed knowledge based genetic algorithm.

The genetic algorithm randomly creates a number of solutions represented by binary strings and are evaluated by the fitness function derived in Eq.(6.4). For f.o.d., l.o.d. and r.o.d. two parent chromosomes are selected from a pool set according to the fitness function and using the three genetic operator reproduction, crossover and bitwise mutation they are modified. This process of iterating a solution using these three operators followed by the fitness evaluation is called a generation. Only on reaching a termination criterion the generation process stops. Here the termination criterion is either the pre-set maximum generation which has to exceed or the best solution which has to remain unchanged for a certain number of generations. Accordingly the command execution moves the robot towards the target by selecting the best heading angle (h.a.).

GA can also be applied to dynamic environment. While in navigation the robot periodically sends in input data of its surrounding using the sensors and if there is a change in the environment it will re-evaluate the current population according to the new surrounding and a new solution will be generated.

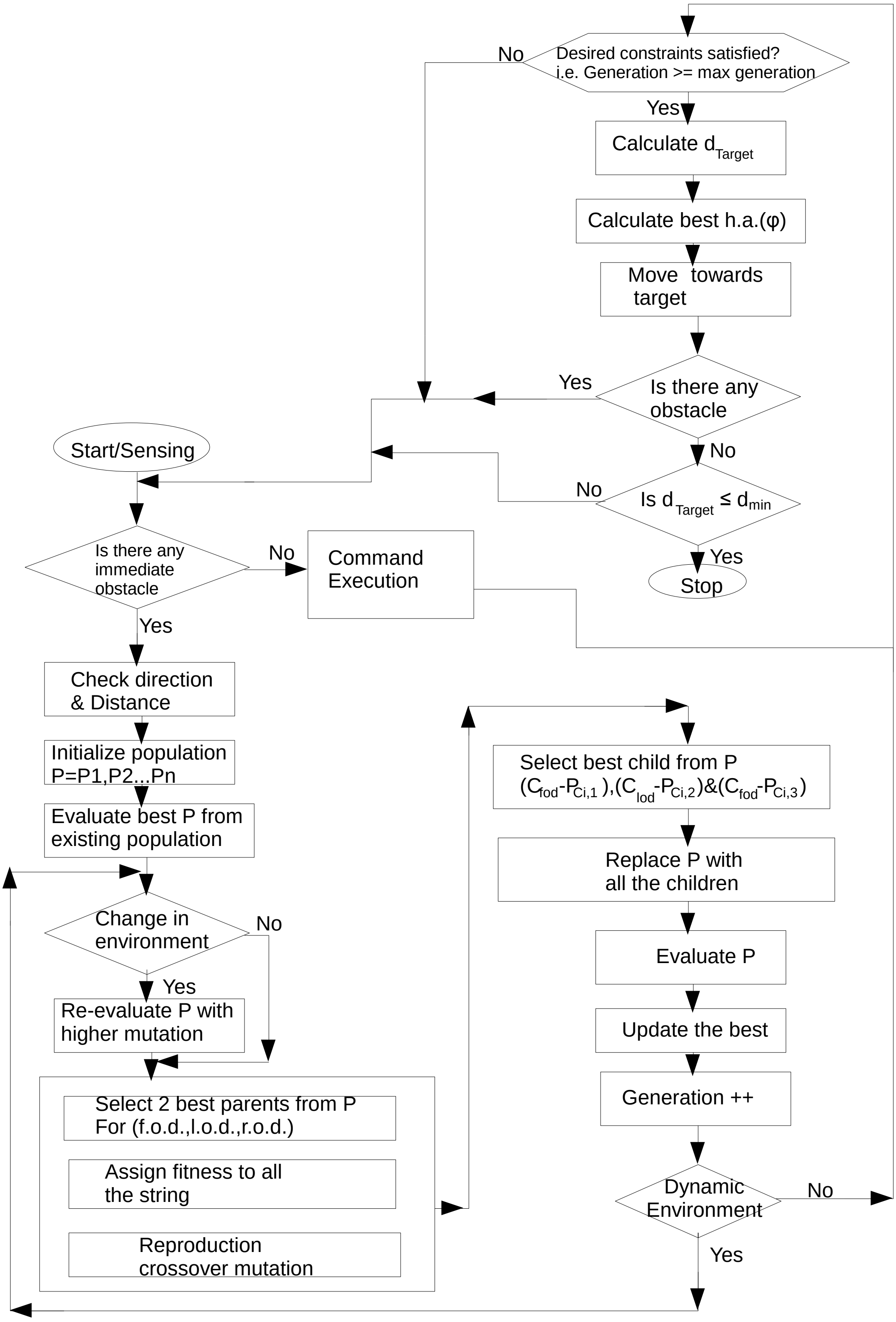


Fig.6.8 Schematic diagram showing the flowchart for the proposed motion planning scheme.

6.3 Results and Discussion

The prime objective of this study was to construct a navigational technique for Mantis and also present an outline of what AI can be implemented in Mantis to optimise its utility and thus enhance its performance from the basic remote controlled prototype. Using the sensor mounted on the robot, inputs from the environment was gathered and processed. Logics derived from fuzzy set theory and genetic algorithm technique were used to write simple Arduino codes by considering obstacle distance from the front, left and right side of the robot as the input to generate optimum heading angle. The theoretical analysis was verified by embedding these control systems into a simulated environment. The results are shown below.

Table 6.6 Result for Path Length Taken during Obstacle Avoidance and target seeking by the Robot

No. of Scenario	*Path Length Using Fuzzy Technique (m)*	*Path Length Using Genetic Technique (m)*	*Experimental Path Length Using Fuzzy Technique (m)*	*Experimental Path Length Using Genetic Technique (m)*
1	2.65	2.55	2.75	2.71
2	3.94	4.01	4.06	4.08
3	2.14	2	2.21	2.19
4	1.69	1.73	1.78	1.81
5	4.18	4.14	4.25	1.19
6	3.19	3.30	3.25	3.41
7	1.15	1.10	1.20	1.16
8	5.28	5.42	5.44	5.53
9	4.52	4.44	4.62	4.58
10	2.75	2.82	2.84	2.91

Table 6.7 Result for Time Taken during Obstacle Avoidance and target seeking by the Robot by the above set of Fuzzy and Genetic Techniques

No. of Scenario	*Time Taken Using Fuzzy Technique (sec)*	*Time Taken Using Genetic Technique (sec)*	*Time Taken in Experiment Using Fuzzy Technique (sec)*	*Time Taken in Experiment Using Genetic Technique (sec)*
1	3.6	9.54	9.18	9.9
2	7.2	14.184	14.436	14.616
3	10.8	7.704	7.2	7.956
4	14.4	6.084	6.228	6.408
5	18	15.048	14.904	15.3
6	4.33	4.48	4.41	4.63
7	1.56	1.49	1.62	1.57
8	7.17	7.36	7.38	7.50
9	6.13	6.02	6.27	6.21
10	3.73	3.82	3.85	3.95

EXPERIMENTAL SETUP

Chapter 7

The design, analysis and fabrication of Mantis was completed successfully. To test the capability of the robot it was put through various experimental setups and these setups are described in this chapter. The basic idea of these tests was to check the mechanisms incorporated in the robot and also to study how the sensors behave and coordinate the motion of the robot. The path traversed by Mantis is documented and the primary task that is to pick-up and drop-off an object as designated is studied under various experimental situations.

These experiments were carried out in the controlled yet cluttered environment of the laboratory. The floor through which Mantis traversed was a very smooth one. From the starting pick-up point to the assigned drop-off point, Mantis had to avoid obstacles in the form of tables and chairs in the laboratory which were covered with white plastic sheets.

Mantis detects obstacles and objects in its path with the help of four ultrasound sensors, two in the front and two at the back and another four infra-red sensors, two each on either side. The Arduino microcontroller used in Mantis is programmed to avoid obstacles and objects in its path and move from the predefined initial pick-up position or co-ordinate (x_1, y_1) to a desired location (x_2, y_2). Mantis uses artificial intelligence (AI) technique to navigate through the dynamic and unstructured environment.

Mantis takes the shortest possible path avoiding obstacles to reach the desired coordinate. The navigation sequence can be divided into two parts: the forward navigation i.e. from the source to destination coordinate and the backward navigation i.e. from the destination to the source coordinate.

7.1 Navigation Sequence for Setup 1

In this set up the robot was made to transport an object of 50x40x20mm size. The designated pick up point was a Rhino Conveyor belt at (1360mm, 6400mm) and the drop-off point was a Rhino Slide Base at (7500, 5200). Some of the coordinates followed by Mantis while target seeking or during forward navigation in the Set-up 1 are shown using photographs (*Fig.7.1*).

Some of the approximate coordinates of the object handled by Mantis in the picture are stated below. The manipulator is picking the object from the pick-up coordinate (1360, 6400) in (*Fig.7.1 a-c*). In (*Fig.7.1d-e*) the mobile platform is turning and heading to the drop-off point, the coordinate in (*Fig.7.1e*) is (2000,6600). At coordinate (3600, 8100) in (*Fig.7.1f*) and coordinate (5300, 8400) in (*Fig.7.1h*) we can see the obstacle avoidance capability of the mobile manipulator. The wall following behavior of the robot is shown from (*Fig.7.1g*) at coordinate (6600,8400) to (*Fig.7.1j*) at coordinate (6300,4800) through coordinate (6300,8000) in (*Fig.7.1i*). At the designated drop-off coordinate (7500, 5200) in (*Fig.7.1 k & l*) the manipulator is dropping off the object.

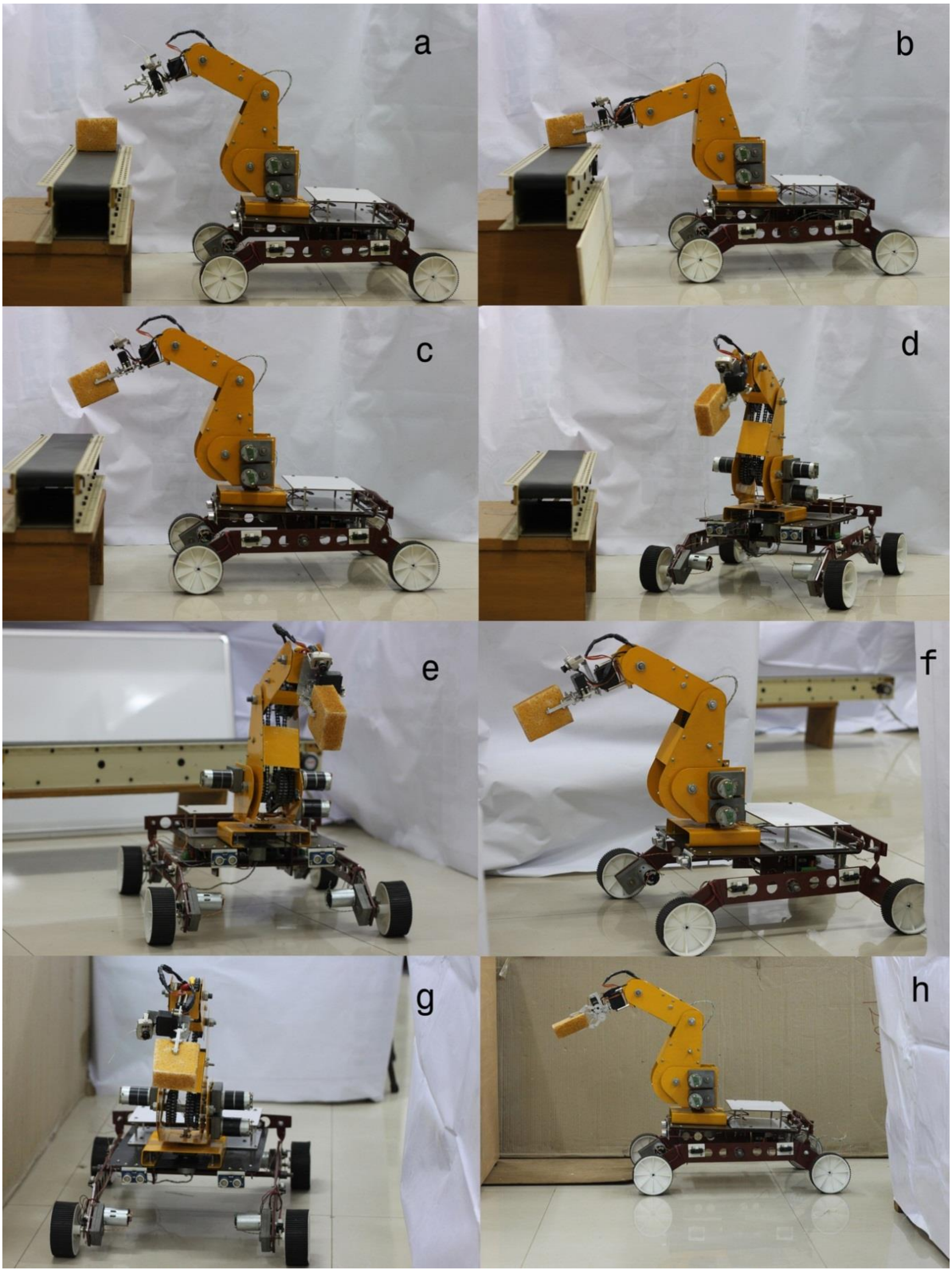


Fig.7.1 Navigation Sequence for Setup 1

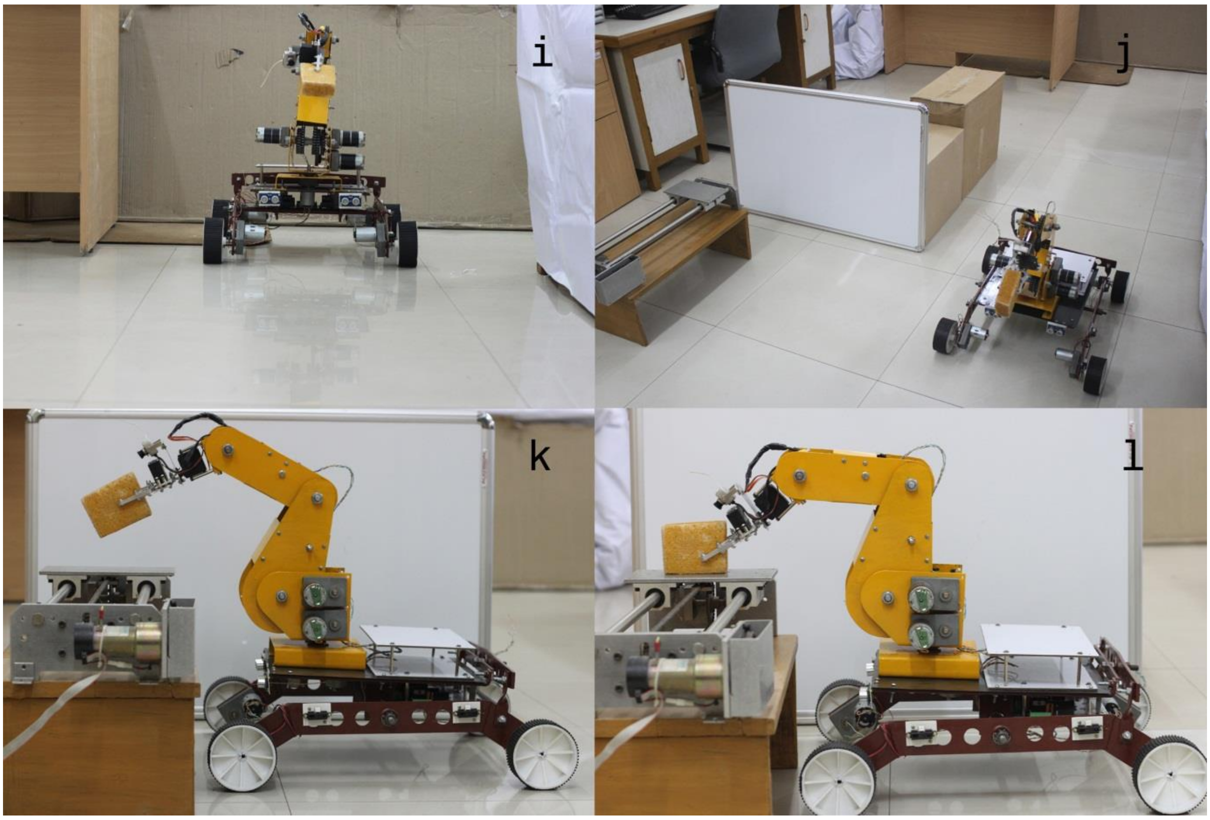


Fig.7.1 Navigation Sequence for Setup 1

In the backward navigation, the path traced by Mantis is an optimised one. Having completed the assigned task Mantis returns back to the pick-up point as seen in (*Fig.7.1m*).

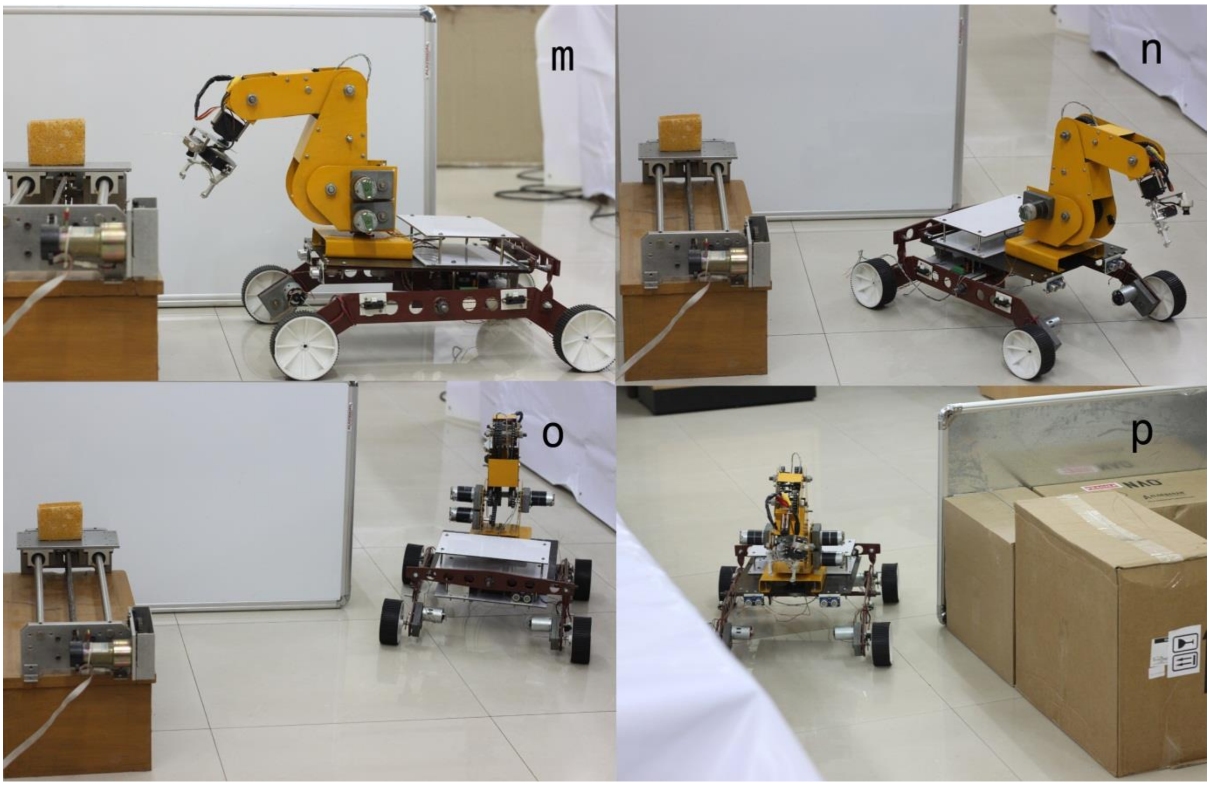


Fig.7.1 Navigation Sequence for Setup 1

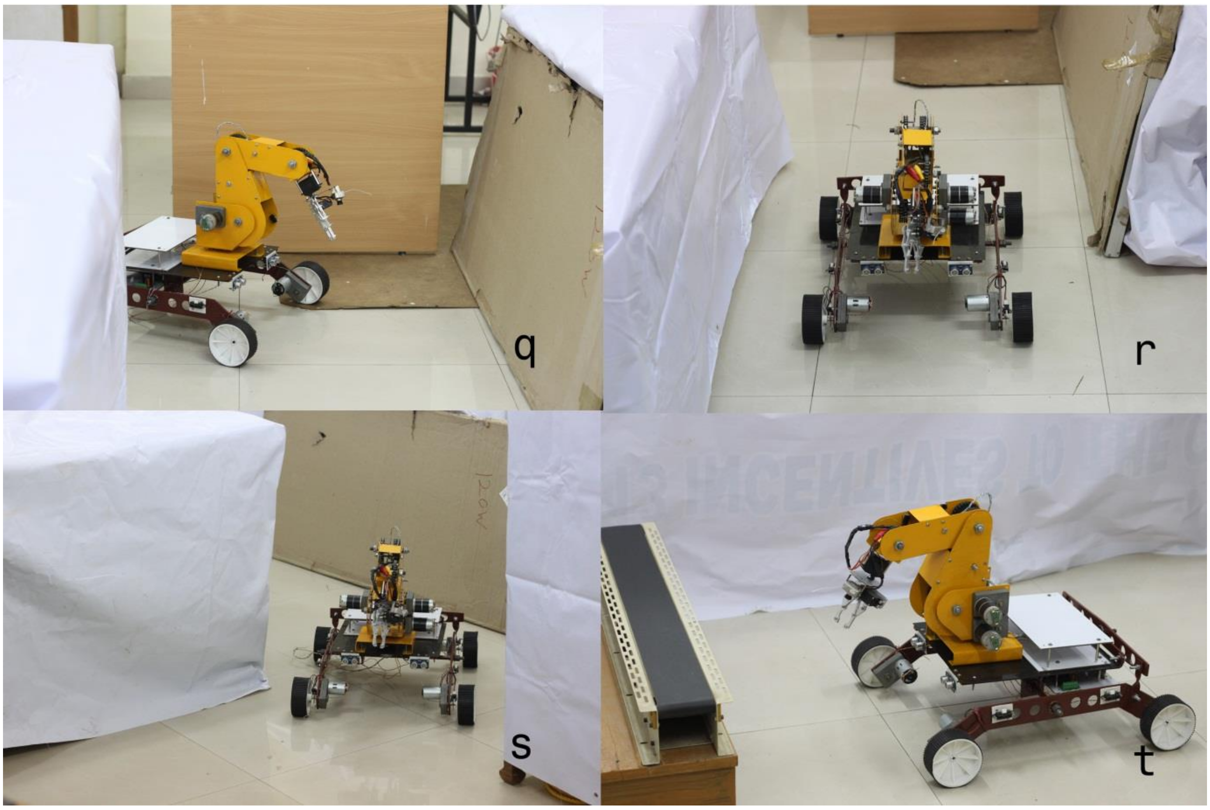


Fig.7.1 Navigation Sequence for Setup 1

The coordinates of Mantis with respect to the end-effector in the photographs are as follows: (6600,4700) in (*Fig.7.1n*), (6300,5500) in (*Fig.7.1 o & p*), (6150,8400) in (*Fig.7.1q*), (5000,8400) in (*Fig.7.1r*), (3600,7700) in (*Fig.7.1s*), (1800,6400) in (*Fig.7.1t*). As in the case of forward navigation, even in the backward navigation we can see the target seeking, obstacle avoidance and wall following behaviour of Mantis.

7.2 Navigation Sequence for Set-up 2

In this set- up the robot was made to transport an object of 60x40x20mm size. The designated pick up point was a Rhino Conveyor belt at (8900, 9600) and the drop-off point was a Rhino Rotary Carousel at (1250, 2250). Similar to set-up 1 some of the coordinates followed by Mantis during target seeking or forward navigation in the Setup 2 are shown using photographs in (*Fig.7.2*).

Some of the approximate coordinates of the object handled by Mantis in the picture are stated below. The manipulator is picking the object from the pick-up coordinate (8900, 9600) in (*Fig.7.2 a-c*). In (*Fig.7.2d*) the object is at coordinate (7950,9000) and here the mobile platform is turning and heading to the drop-off point. At coordinate (6800, 7800) in (*Fig.7.2e*), (6850, 3300) in (*Fig.7.2h*) and (1250,3300) in (*Fig.7.2k*) we can see the obstacle avoidance capability of the mobile manipulator. The wall following behavior of the robot is shown in (*Fig.7.2f*) at coordinate (6850, 7500), in (*Fig.7.2g*) at (6850, 4500) and in (*Fig.7.2j*) at (3900,3300).

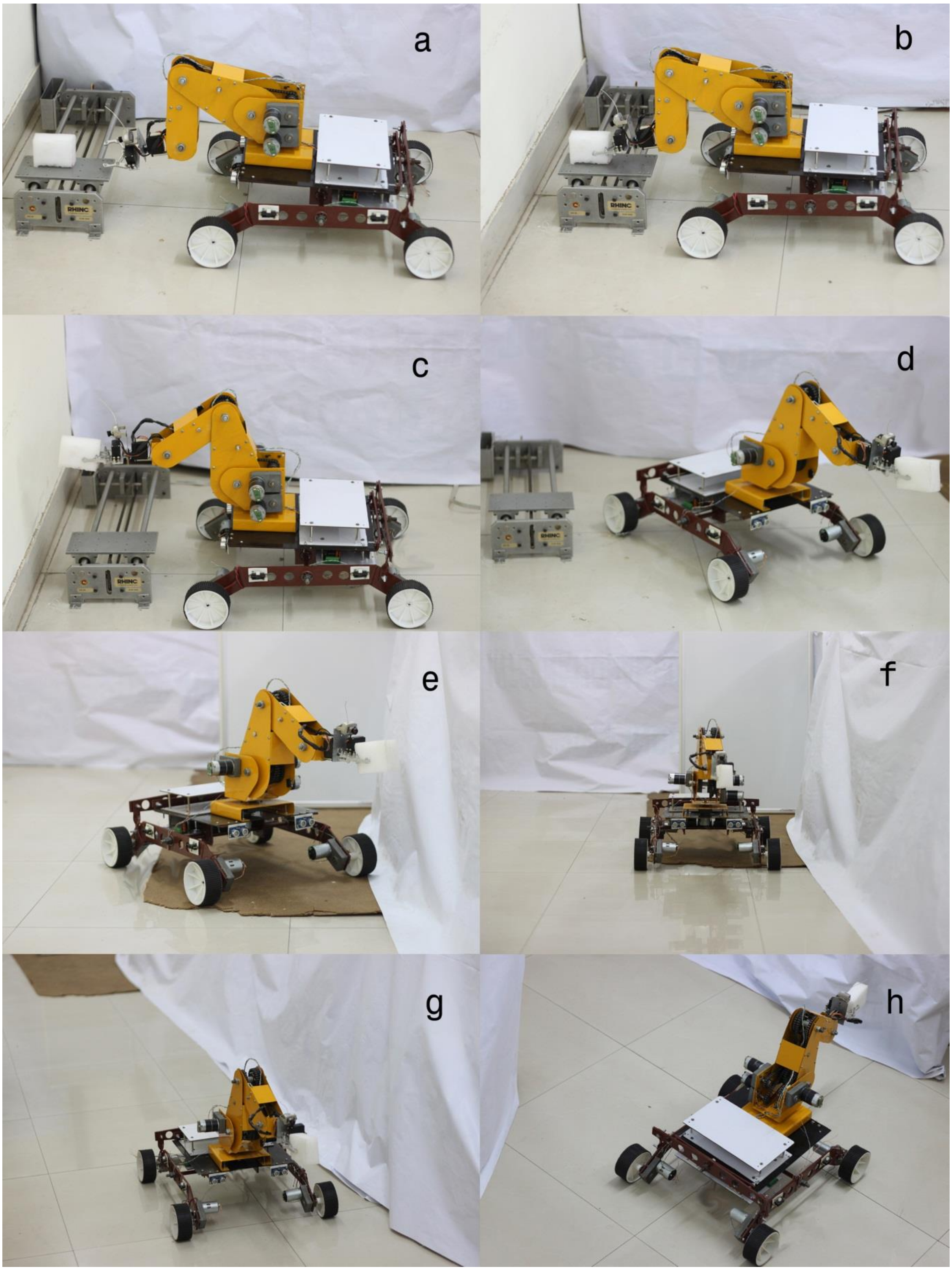


Fig.7.2Navigation Sequence for Setup 2

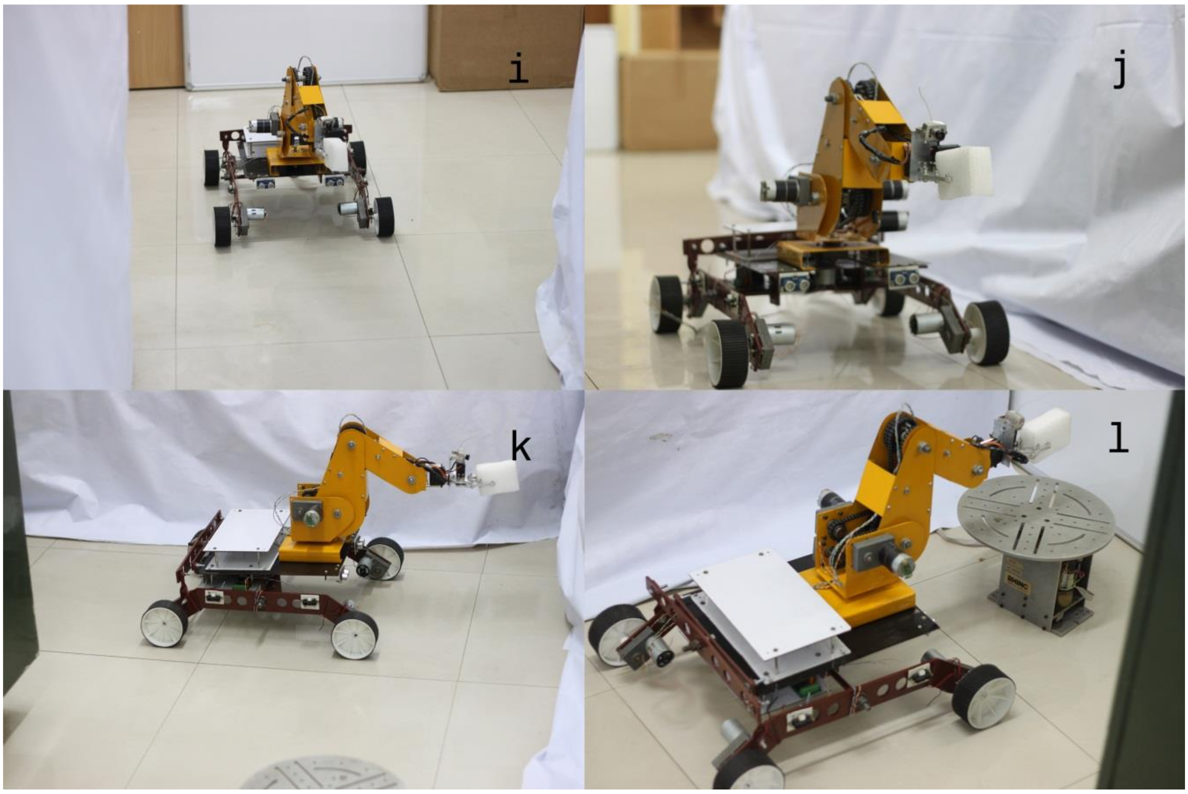


Fig.7.2Navigation Sequence for Setup 2

At the designated drop-off coordinate (1250,2250) in (*Fig.7.2 l & m*) the manipulator is dropping off the object.

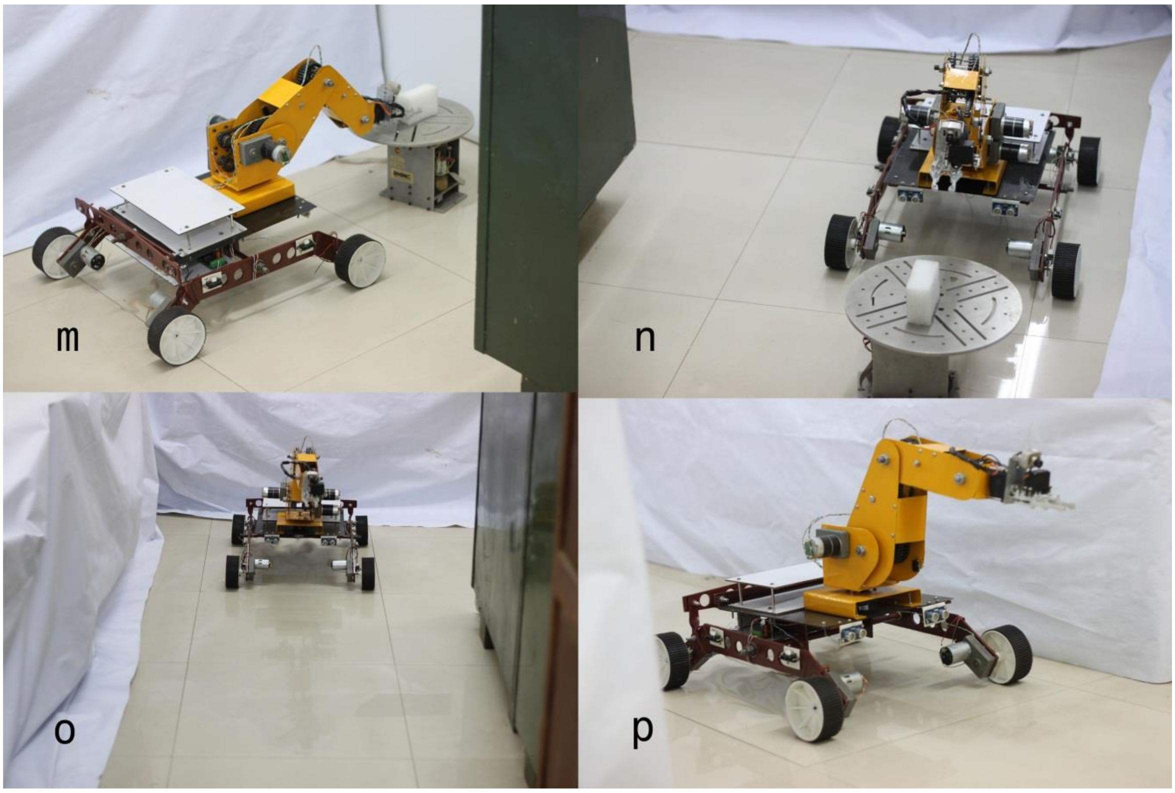


Fig.7.2Navigation Sequence for Setup 2

Mantis starts to return back to the pick-up point as seen in (*Fig.7.2n*) after dropping off the object. The obstacle avoidance, target seeking and wall following behaviour of the robot is exhibited even in the backward navigation. And some of the coordinates of Mantis with respect to the end-effector on its way back shown in the photographs are as follows: (1800,3300) in (*Fig.7.2o*), (6200,3300) in (*Fig.7.2p*), (7200,3900) in (*Fig.7.2q*), (7350,5400) in (*Fig.7.2r*), (7350,8100) in (*Fig.7.1s*), (8900,9600) in (*Fig.7.1t*).

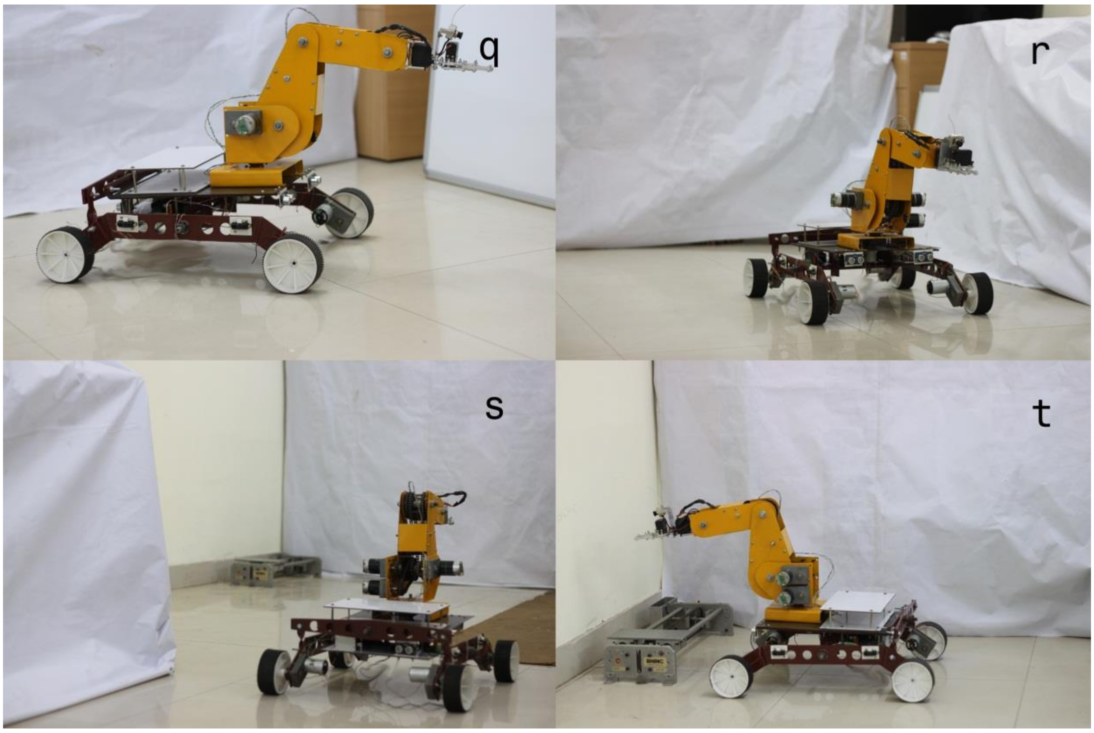


Fig.7.2Navigation Sequence for Setup 2

7.3 Outdoor Testing

Fig.7.3Outdoor Testing 1

Mantis was taken outside to test its mechanisms and to check its performance in different working conditions (*Fig.7.3*). Unlike the controlled and orderly environment of the laboratory the outdoor conditions are dynamic and random hence it is much more challenging.

The photograph shown below (*Fig.7.4*), highlights the performance of Mantis's suspension system which is a grand success and also drive mechanism of the mobile platform which enables Mantis to climb an inclined plane of 25^{o}.

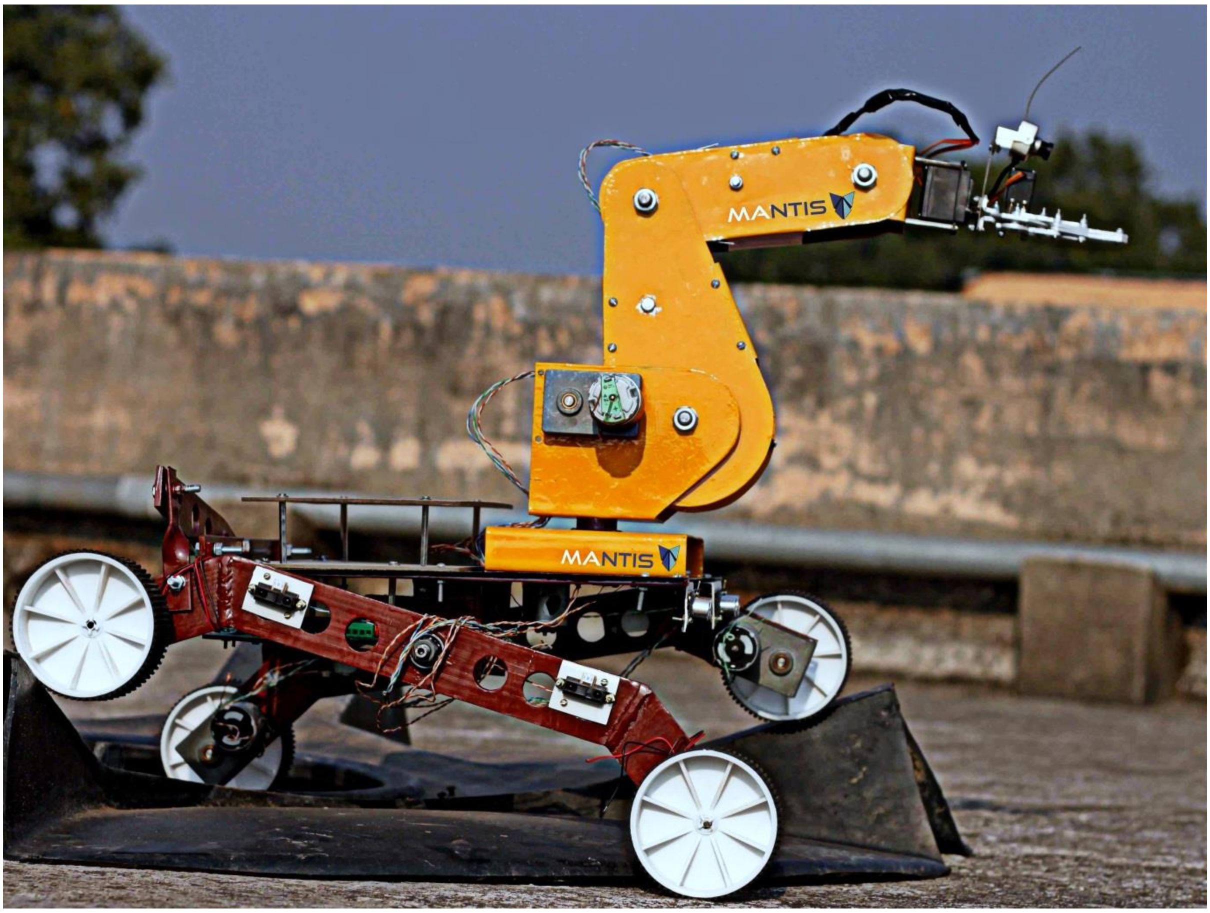


Fig.7.4Outdoor Testing 2

7.4 Conclusion

Implementation of the AI techniques presented in the previous chapter using basic Arduino codes has been presented in this chapter. This is a very rudimentary approach in automating Mantis and has a lot of scope to improve in future. Through different experimental setups, which includes both indoor and outdoor setups the capabilities of Mantis has been demonstrated.

CONCLUSION

Chapter 8

8.1 Nomenclature

8.2 Characteristics of the Project

8.3 Conclusion and Future work

8.4 Patent Details

CONCLUSION

The target is successfully completed by designing, analysing and fabricating Mantis, an articulated robotic manipulator on a mobile robotic platform.

8.1. Nomenclature:

Mantis is considered to be an auspicious, harmless, gentle orthopterous carnivorous insect, which is commonly known as praying Mantis, because of its large spinous forelegs kept in praying posture, which gives it a humble look. The outstretched Manipulator of the robot gives it a Mantis like appearance which upholds its simplicity & humbleness.

8.2. Characteristics of the Project:

- The Design of the robot
- Low cost of production
- Use of readily available material
- Easy fabrication processes
- The performance of the robot

The main characteristic of this work is the unique design implemented for fabricating it. The robot has a robust built and is equipped to use in uneven terrains.

The processes involved in designing, analysing and fabricating the mobile robotic manipulator have been explained in different chapters. The model was designed according to the specification, considering various factors like: cost of production, readily available material, machining ease, quick replacement in case of damage, etc. The design basically comprises of two parts, the robotic manipulator/arm which is fixed on to the mobile platform and was programmed using Arduino®, the AVR based microcontroller. The objective of developing this remotely controlled mobile robotic manipulator is for handling materials weighing up to 500gms. Though built for pick and place application, interestingly it could be reconfigured without difficulty to do other jobs like drilling, welding, inspection, vacuuming, etc.

Detailed literature survey was conducted by studying more than 85 literature/papers relating to robotic manipulators, mobile robots and also kinematic analysis of robotic systems. This is clearly indicated in chapter -2 of this thesis. Information was also collected from internet, and studying design principles behind numerous robots available in the market and in the laboratories.

After deciding the target, specifications for the same were drafted and the details given in chapter -3. It was divided into two separate sections, one dealing with the design specification of the robotic manipulator and the other dealing with the design specification of the mobile robotic platform. The various manipulator parts were decided by considering its motion, then its links & joints with end effector was finalized. In this section we have finalized sizes/ basic dimensions of the manipulator and its rotation angle of each links. The total kinematic analysis of the project is detailed here. The study of kinematics of the manipulator helps us to understand the relationship between the position and orientation of the end-effector and the joint variables. The drive mechanism for robot is decided considering various options, and we have finalized the manipulator to use electric powered DC motors and servo motors for actuation with a set of mechanical power trains which consists of chains and sprockets.

The mobile platform adopts a novel suspension system. It was fixed with four wheels powered by four high torque DC motors and works on the principle of skid-steer. The required basic dimensions of the platform are specified here in chapter-3.

Any product's final look will increase its value in the market. Special care was taken to give a beautiful look to Mantis.Chapter-4 deals with the design and modeling of the mobile robotic manipulator. Modeling of Mantis was a tough task, initially few preliminary designs were created and from which one design that best suited our requirement and specification was chosen. Base of the Robotic Manipulator, body of the Robotic Manipulator, the Arm Link 1 (Upper-arm) of the Robotic Manipulator, the Arm Link 2 (Forearm) of the Robotic Manipulator are the main created parts of Mantis. The dimension was finalized based on specification and the manipulator of Mantis was assembled to set all the drives in place and this is clearly given in chapter -4.

Materials for themanipulator and the mobile robot were selected to withstand all the forces and weights acting on it. The fabrication of the manipulator was done with galvanized sheet of different thicknesses and the same was bend/shaped with required holes and machined to suite the assembly with motor and other components, which is detailed in chapter -5.Similarly the design and fabrication of the parts for the suspension system was the main task in building the mobile robotic platform. Mild steel flats of 5mm thickness with different width shaped to required size were used in fabricating the suspension system for the mobile platform of Mantis and then mild steel shafts with drives were fixed for mobility. Production cost was the main criteria for the selection of above material for Mantis.

Use of readily available materials and easy fabrication processes are another two important characteristics of Mantis, which are given in Chapter -5. The total machining processes were done in the institute workshops.

The most interesting animal on this planet earth is man. There is nothing else to be compared to him. This superiority which is resulted from his intelligence fascinated him so much that he tried to mimic his capacities in his own creations/inventions. The result was man-machine or robot. Intelligence which makes man different from other animals makes robot also different from other machines. Artificial intelligence (AI) which is the brain of a robot, makes it function as it is intended to do.AI includes many techniques like fuzzy logic control, genetic algorithm etc. Rule based fuzzy logic mimics the decision making and reasoning capability of human beings with imprecise and inexact information. Genetic algorithm is based on the mechanics of biological evolution and is designed to develop system that has the robustness and adaptive capability of natural systems and understand processes involved in natural system. These are the AI techniques used in this mobile robotic manipulator Mantis, which is detailed in chapter-6.

The smooth performance of Mantis is described in chapter -7. To test the capability of Mantis, it was put through various experimental setups inside the laboratory and through a rough terrain test outside the laboratory conditions.

8.3. Conclusion & Future Work:

In the current research design, analysis, fabrication and navigational path planning for a mobile robotic manipulator has been successfully carried out. During the research a mobile robot was designed and developed in the laboratory, along with it a robotic arm has also been designed and developed to carry out pick and place task in a dynamic and unknown environment.

For carrying out the path planning in dynamic environment mobile robot kinematics and robotic arm kinematics has been carried out and it has been discussed. Also, the mathematical formulae for the same have been given and corresponding results were shown in real mode.

For carrying out the path planning, fuzzy logic and genetic algorithm techniques are analysed. Navigational controls are built using fuzzy logic and genetic algorithm with the help of the sensors' information so that the robot can negotiate obstacle while carrying out various tasks in an unknown environment. The results are experimentally validated and are found to be in agreement. In future, more robust artificial algorithm will be implemented to control the navigational path of the currently developed mobile robot in a dynamically cluttered environment.

Though Mantis is designed to perform pick and place task, it can be modified to do a variety of tasks. Since the end-effector can be easily detached from the arm and also the whole manipulator can be detached from the mobile platform, multiple tasks like drilling, welding, vacuuming, etc. can be realised with Mantis. Modified version of Mantis with more capacity can be used for pick and place task in hospitals, supermarkets, libraries, laboratories, warehouses etc. which have even surfaces and also in uneven surfaces like loading and unloading from vehicles, in construction sites, during rescue operations in fire-fighting and other natural calamities ,military operations, space researches etc. Nevertheless, there is a scope for further study and improvisation of the system for better use in the future.

8.4. Patenting of project:

The unique design implemented for fabricating this robot is distinct from other robots. The mobile manipulator designed and fabricated has a 5 – axis articulated arm for pick and place application which can be reconfigured to do other tasks. The manipulator is built with its driving or power sources fitted at the bottom to distribute the load evenly and also make handling easier. The mobile platform employs a novel suspension system which helps in distributing the load equally to all wheels regardless of the wheel position giving the mobile platform better control and stability. With reference to many available manipulators and mobile platforms in the market, a practical design was conceived using designing tools and a fully functional prototype was fabricated.

Hence patenting of this project is considered and application and other necessary details are being submitted to the authorities for scrutiny.

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APPENDIX 1

The table below states the ANSI standard for Roller Chains which was used to select the chains stated in this work.

ANSI B29.1 Roller Chain Standard Sizes

Size	Pitch	Roller diameter	Tensile strength	Working load
25	0.250 in (6.35 mm)	0.130 in (3.30 mm)	781 lb (354 kg)	140 lb (64 kg)
35	0.375 in (9.53 mm)	0.200 in (5.08 mm)	1,758 lb (797 kg)	480 lb (220 kg)
41	0.500 in (12.70 mm)	0.306 in (7.77 mm)	1,500 lb (680 kg)	500 lb (230 kg)
40	0.500 in (12.70 mm)	0.312 in (7.92 mm)	3,125 lb (1,417 kg)	810 lb (370 kg)
50	0.625 in (15.88 mm)	0.400 in (10.16 mm)	4,880 lb (2,210 kg)	1,430 lb (650 kg)
60	0.750 in (19.05 mm)	0.469 in (11.91 mm)	7,030 lb (3,190 kg)	1,980 lb (900 kg)
80	1.000 in (25.40 mm)	0.625 in (15.88 mm)	12,500 lb (5,700 kg)	3,300 lb (1,500 kg)
100	1.250 in (31.75 mm)	0.750 in (19.05 mm)	19,531 lb (8,859 kg)	5,072 lb (2,301 kg)
120	1.500 in (38.10 mm)	0.875 in (22.23 mm)	28,100 lb (12,700 kg)	6,800 lb (3,100 kg)
140	1.750 in (44.45 mm)	1.000 in (25.40 mm)	38,280 lb (17,360 kg)	9,040 lb (4,100 kg)
160	2.000 in (50.80 mm)	1.125 in (28.58 mm)	50,000 lb (23,000 kg)	11,900 lb (5,400 kg)
180	2.250 in (57.15 mm)	1.460 in (37.08 mm)	63,300 lb (28,700 kg)	13,700 lb (6,200 kg)
200	2.500 in (63.50 mm)	1.562 in (39.67 mm)	78,000 lb (35,000 kg)	16,000 lb (7,300 kg)
240	3.000 in (76.20 mm)	1.875 in (47.63 mm)	112,500 lb (51,000 kg)	22,250 lb (10,090 kg)

Papers Published/Accepted/Communicated in Journals/Conferences & Patent Work

1. J.Srinivas and E.Eliot, “Design of Articulated Arm for In-Vessel Inspection Systems”, In Proc. of National Conference on Emerging Trends in Mechanical Engineering (ETME-2012), Bhopal, India, pp.8-11, Nov. 2012.
2. E.Eliot, D.R.Parhi and J.Srinivas, “Design & Kinematic Analysis of an Articulated Robotic Manipulator”, In Proc. of International Conference on Mechanical and Industrial Engineering (ICMIE-2012),Goa, India, Apr.2012.
3. E.Eliot and D.R.Parhi “An Overview on Designing, Analysing and Fabricating a 5-Axes Articulated Robotic Manipulator”, International Journal of Applied Intelligence in Engineering Systems, pp.133-138, Vol.3 No.2 2011
4. E.Eliot and D.R.K.Parhi, “*Mobile Robotic Manipulator*”, patent has been filed for this work at Indian Patent Office, Kolkata. Filing Number: 1020/KOL/2013.

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AREA OF INTEREST

Product Design & Development, Mechanism & Machineries, Robotics & Automation, Mechatronics.

EDUCATION

National Institute of Technology Rourkela Jan.2011 – Present
Master of Technology by Research in Industrial Design (9.44 CGPA)
Thesis submitted, awaiting review result.

NMAM Institute of Technology, Nitte Sept.2006 – May 2010
Visvesvaraya Technological University, Belgaum
Bachelor of Engineering in Mechanical Engineering (1st Class)

St. Aloysius College, Mangalore Jun.2004 – Mar.2006
Pre-University (84.83%)

Milagres Junior College, Mangalore Apr.2004
SSLC (82.88%)

TOOLS

AutoCAD, CATIA V5, SolidWorks, ANSYS, Arduino, Photoshop, C/C++.

PATENT

A patent is being filed for the M.Tech project: *Design, Analysis and Fabrication of an Articulated Mobile Manipulator* under the name "*Articulated Mobile Robotic Manipulator: Mantis*"

PROJECTS

Design, Analysis and Fabrication of an Articulated Mobile Manipulator Jan. 2011 – Present
Design and fabrication of a 5 axes articulated robotic manipulator on an articulated rover, suitable for versatile environment with multiple applications. It includes kinematic analysis of the fully functional product.

Design of an Articulated Manipulator for In-vessel Inspection in a TOKAMAK Sept.2012 – Mar.2013
As part of BRFST research work on fusion reactors, an articulated robotic arm is to be designed for the inspection of the first wall of a nuclear fusion reactor device (TOKAMAK) for a hostile environment.

Design of an Under-Water Robot Jun.2012 – Jan.2013
Using CATIA generated a design for an under-water robot.

Design of a 3 RPR Mechanism Jan.2012 – Jun.2012
Generated 3D designs using CATIA to animate and simulate a 3 RPR mechanism.

Single Motor Multiple Joint Actuation Mechanism Jan.2012 – May 2012
Designed a mechanism which can operate multiple joints in multiple planes with a single motor.

Design and Fabrication of a Device for Rubber Tapping Sept.2009 – Jun.2010
A novel design for a rubber tapping device to tackle the problems faced by rubber tappers.

Gravity Groove Jan.2009

First place, TechFest, IIT, Bombay.

A fantasy rollercoaster model making competition working purely on gravity with maximum number of vertical and horizontal loops.

Rube Goldberg Contraptions Feb.2009

First place, AISIRI, 10th Annual VTU Youth Festival

Rube Goldberg Contraption is a complicated device or a set of devices, arranged in such a way that a simple task is executed in a complex and indirect way.

CONFERENCES & EXPOSURES

Mission to Israel on Robotics and Automation Mar.2012

Visited Israel as a part of the *CII National Committee on Robotics and Automation* delegation, to create a sustainable environment for the growth of robotics and automation technology in India.

National Conference On Emerging Trends In Mechanical Engineering (ETME), Bhopal Nov.2012

WORKSHOPS & TRAINING PROGRAMMES

Workshop on ***Modeling and Analysis of Dynamic Systems***, jointly conducted by the Department of Applied Mathematics and Department of Mechanical Engineering, NIT Rourkela. Dec.2011

Participated in LogiTRIx, ***Advanced Autonomous Robotics Workshop***, conducted by ThinkLABS SINE IIT Bombay at NMAMIT, Nitte. Nov.2009

Training programme in ***Hydraulics and Pneumatics*** conducted by the VTU - Bosch Rexroth Centre of Competence in Automation Technology, Mysore. Sept.2009

PUBLICATIONS

J.Srinivas and E.Eliot, “Design of Articulated Arm for In-Vessel Inspection Systems”, In *Proc.* of *National Conference on Emerging Trends in Mechanical Engineering* (ETME-2012), Bhopal, India, pp.8-11, Nov. 2012.

E.Eliot, D.R.Parhi and J.Srinivas, “Design & Kinematic Analysis of an Articulated Robotic Manipulator”, In *Proc.* of *International Conference on Mechanical and Industrial Engineering* (ICMIE-2012),Goa, India, Apr.2012.

E.Eliot and D.R.Parhi “An Overview on Designing, Analysing and Fabricating a 5-Axes Articulated Robotic Manipulator”, *International Journal of Applied Intelligence in Engineering Systems*, pp.133-138, Vol.3 No.2 2011.